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Postglacial Environmental Conditions, Vegetation Succession and Human Impact in Latvia

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Declaration: *Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for doctoral or equivalent academic degree.*

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LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following papers, referred to in the text with Roman numerals as listed below.

Paper I Veski, S., Amon, L., Heinsalu, A., Reitalu, T., Saarse, L., **Stivrins, N.**, Vassiljev, J. 2012. Lateglacial vegetation dynamics in the eastern Baltic region between 14,500 and 11,400 cal yr BP: A complete recorded since the Bølling (GI-1e) to the Holocene. Quaternary Science Reviews, 40: 39–53.

Paper II Stivrins, N., Kalnina, L., Veski, S., Zeimule, S. 2014. Local and regional Holocene vegetation dynamics at two sites in eastern Latvia. Boreal Environment Research, 19: 310–322.

Paper III Stivrins, N., Brown, A., Reitalu, T., Veski, S., Heinsalu, A., Banerjea, R.Y., Elmi, K. 2014. Landscape change in central Latvia since the Iron Age: multi-proxy analysis of the vegetation impact of conflict, colonization and economic expansion during the last 2000 years. Vegetation History and Archaeobotany, (available online 21. November 2014), DOI:10.1007/s00334-014-0502-y.

Paper IV Veski, S., Seppä, H., Stančikaitė, M., Zernitskaya, V., Reitalu, T., Gryguc, G., Heinsalu, A., **Stivrins, N.**, Amon, L., Vassiljev, J., Heiri, O. 2014. Quantitative summer and winter temperature reconstructions from pollen and chironomid data between 15–8 ka BP in the Baltic–Belarus area. Quaternary International, (available online 26. November 2014), DOI:10.1016/j.quaint.2014.10.059.

Paper V Stivrins, N., Kołaczek, P., Reitalu, T., Seppä, H., Veski, S. Phytoplankton response to the environmental and climatic variability in a temperate lake over the last 14,500 years. Journal of Paleolimnology (submitted manuscript).

Paper VI Stivrins, N., Brown, A., Veski, S., Ratniece, V., Heinsalu, A., Austin, J., Liiv, M., Ceriņa, A. Palaeoenvironmental evidence for the impact of the crusades on the local and regional environment of medieval (13^{th}–16^{th} century) northern Latvia, eastern Baltic. The Holocene (submitted manuscript).

The author's contribution: contributing in fieldworks and laboratory analyses (Papers I–VI), pollen analysis and contributing in interpretation of palaeobotanical data (Papers I, II, III, VI), compilation of diagrams, tables and figures (Papers II, III, V, VI), loss-on-ignition analysis (Papers II, III, V), non-pollen palynomorphs analysis and interpretation (Paper III, V), magnetic susceptibility measurements (Paper III, V, VI), spheroidal fly-ash particle analysis (Paper III), age-depth modelling (Papers II, III, V, VI), responsible for preparing the manuscript (Papers II, III, V, VI).

Related publication not included in this thesis:

Kalnina, L., **Stivrins, N.**, Kuske, E., Ozola, I., Pujate, A., Zeimule, S., Grudzinska, I., Ratniece, V. 2014. Peat stratigraphy and changes in peat formation during the Holocene in Latvia. Quaternary International, in press, http://dx.doi.org/10.1016/j.quaint.2014.10.020.

ABBREVIATIONS

a.s.l. – above the sea level
AD – calendar age after Christ, *Anno Domini*
AMS – accelerator mass spectrometry
AR – accumulation rate
BC – calendar age before Christ
cal BP – calibrated years before present (AD 1950)
GI-1 – Greenland Interstadial 1
GS-1 – Greenland Stadial 1
HTM – Holocene Thermal Maximum
ICP-OES – inductively coupled optical emission spectroscopy
LG – Lateglacial
LOI – loss-on-ignition
MM – mineral matter
MS – magnetic susceptibility
OM – organic matter
PCA – Principal Components Analysis
RDA – Redundancy Analysis
SFAP – spheroidal fly-ash particles dating
T_{sum} – mean summer air temperature
T_{win} – mean winter air temperature
WA-PLS – weighted averaging partial least squares

INTRODUCTION

Pollen grains preserved in lake and bog deposits serve as one of the most powerful tools for reconstructing past vegetation and environment. Following the elaboration of pollen analysis in 1916 by Lennart von Post (von Post 1916), pioneering palynological research was also initiated in the Baltic region (Thomson 1922, 1929; Nomals 1930; Galenieks 1931, 1935). Numerous palynological studies from bog and lake sediment sequences have been carried out in Latvia since then (Danilans 1955; Levkovskaya 1987; Lācis and Kalniņa 1998; Kalnina et al. 2004; Ozola et al. 2010; Ozola 2013). The majority of the postglacial sequences in Latvia, however, are still not dated and are described solely through comparisons of pollen zones. To-date, there are only some chronologically controlled pollen sequences from lakes in Latvia (Heikkilä and Seppä 2010; Puusepp and Kangur 2010). Due to the lack of a defined time scale, uncertainty remains with respect to the relative timing of environmental changes in relation to climate variability during the LG and Holocene. Therefore, many questions remain, particularly regarding the succession of local and regional vegetation, palaeoenvironmental conditions and climate change.

Palaeoecological records preserved in sedimentary deposits such as lakes provide unique insights into the history of past ecosystems and long-term plant community dynamics. Relatively small and closed lakes with undisturbed and continuous sedimentation possibly integrate the majority of the information about the changes in the lake basin and its catchment (Seppä et al. 2009).

All of the sites studied for this thesis are situated in Latvia and lie between the oceanic and continental climate regions and in the boreo-nemoral ecotonal transitional zone, which is more sensitive to environmental changes and can be stronger represented *via* a variety of proxies preserved in the lake sediments. In this regard, the sites selected for this thesis are important in a wider regional context. Furthermore, the longest and most complete record of postglacial vegetation history in Latvia is presented to reconstruct the past millennial scale changes, which could add to further case studies on vegetation dynamics and be integrated into models.

Sugita (2007) has shown that relatively small lakes and stand-scale sites better reflect changes in the immediate vegetation than large lakes, where long-distance effects of pollen cannot be overlooked (Broström et al. 2008; Kuneš et al. 2008). The sizes of the studied lakes vary from 13–32.6 ha, thus the pollen source areas are comparable. Studies of stand-scale sites situated under a closed canopy have proven to be useful for recording vegetation history within an approximate radius of 20–100 m from the site (Overballe-Petersen and Bradshaw 2011). Palaeoecological investigations have shown the possibilities of stand-scale sites to reflect disturbances and tree succession patterns that can be linked directly to past local vegetation (Bradshaw et al. 2005; Bjune et al. 2009). Comparisons between two sites that are situated close to each other but have different pollen source areas may reflect differences and let us evaluate possible factors that control the development of vegetation at the local and regional scale. However, the question remains: what is the role of the local *versus* regional changes in vegetation dynamics in Latvia?

In addition to postglacial vegetation succession, environmental changes and climatic variability, lake sediments preserve evidence of the anthropogenic activity. Although humans have inhabited Latvia since the Paleolithic (Loze 1972, 1997, 2003; Levkovskaya 1987; Vasks et al. 1999; Ozola et al. 2010; Meadows et al. 2014a, 2014b), there are few detailed studies of land-use history and human impact on local and regional environments in the area. Since the proposal of the "*landnam*" theory by Iversen (1941) and publication on anthropogenic pollen indicators by Behre (1981), detection of human presence and activities in certain areas has become possible. Palaeoenvironmental studies (e.g., Poska et al. 2004; Poska and Saarse 2006; Saarse et al. 2010; Heinsalu and Veski 2010), particularly pollen analysis, have shown that it is possible to recognize and reconstruct local agricultural history and human-induced landscape changes even when signs of early cultivation are weak. This may also serve to explain archaeological issues and questions by adding evidence from another perspective: when did the first intensive cultivation practices begin in Latvia, and what was their magnitude in comparison to later times? Can we differentiate the Iron Age cultivation pattern from medieval patterns, where in addition to new field systems and techniques, political change appeared with the foreign crusades (Curry 2012; Brown and Pluskowski 2014)? Did noticeable changes in land ownership (the crusades) actually change previous agricultural practises, and how different were those changes in Latvia compared to other regions during the invasion of the crusades?

Human-induced changes mainly increase of agricultural and industrial development, has promoted nutrient overenrichment of waters (eutrophication), which can negatively impact water quality. Furthermore, a rise in mean air temperature can influence the stratification of lake water columns and initiate dominant toxic algal blooms of cyanobacteria (Brookes and Carey 2011; Winder and Sommer 2012; De Senerpont Domis et al. 2013; Lürling et al. 2013; Pätynen et al. 2014). Phytoplankton species are the primary producers of biomass in lakes, and they play important role in a variety of food-web structures. Any shift in their diversity and production has an impact on other aquatic life forms. Therefore, it is crucial to improve our understanding of how natural temperate terrestrial and aquatic ecosystems responded to long-term postglacial climate and environmental change, to predict their response to future environmental variability. There are, however, few studies on fossil phytoplankton (excluding diatoms), such as green algae and cyanobacteria (Veski 1994; van Geel et al. 1996; Jankovská and Komárek 2000; Weckström et al. 2010), which increases the importance of other microfossil components that are visible during pollen analysis. Commonly these "other" microfossils are called non-pollen palynomorphs (van Geel 2001), and the palaeoecological community has become increasingly interested in examining them.

The natural ecosystem is complex, and in many cases mono-analysis cannot truly reflect all environmental changes. Therefore, a multi-proxy approach was applied for most of the studied sites related to this thesis to determine vegetation dynamics, environmental and climatic change, and also human impacts on lakes and their surroundings. Taking a long term and multi-proxy approach offered by the palaeoenvironmental record, the results of this thesis allow the new data to be placed within a broader environmental, cultural and historical context in the eastern Baltic region.

The aims of the present thesis are as follows:

1. to discuss the temporal and spatial magnitude of climate variability during the LG and the Early Holocene;
2. to reconstruct the longest and most complete postglacial record of vegetation history in Latvia and discuss local and regional Holocene vegetation dynamics;
3. to evaluate for the first time in the Baltic region which environmental factors influenced the dominance of specific phytoplankton communities over the last 14,500 cal BP;
4. to reconstruct the establishment of intensive land-use and evaluate changes in vegetation and environment with the start of agricultural practice in Latvia;
5. to assess the impact of humans on the local and regional terrestrial environment before and after the conquest of the crusades (13^{th}–16^{th} century).

1. MATERIAL AND METHODS

1.1. Study area and sites

The geographical location of study area, Latvia, is 55°40’ to 58°05’N and 20°58’ to 28°14’E and is bordered by Estonia to the north, Russia to the east, Belarus to the southeast and Lithuania to the south (Fig. 1). The western and northwestern coasts of Latvia are surrounded by the Baltic Sea. Latvia’s area is 64,589 km^2, of which approximately 10% is covered by peatlands and 4% by rivers and lakes (Kalnina et al. 2014).

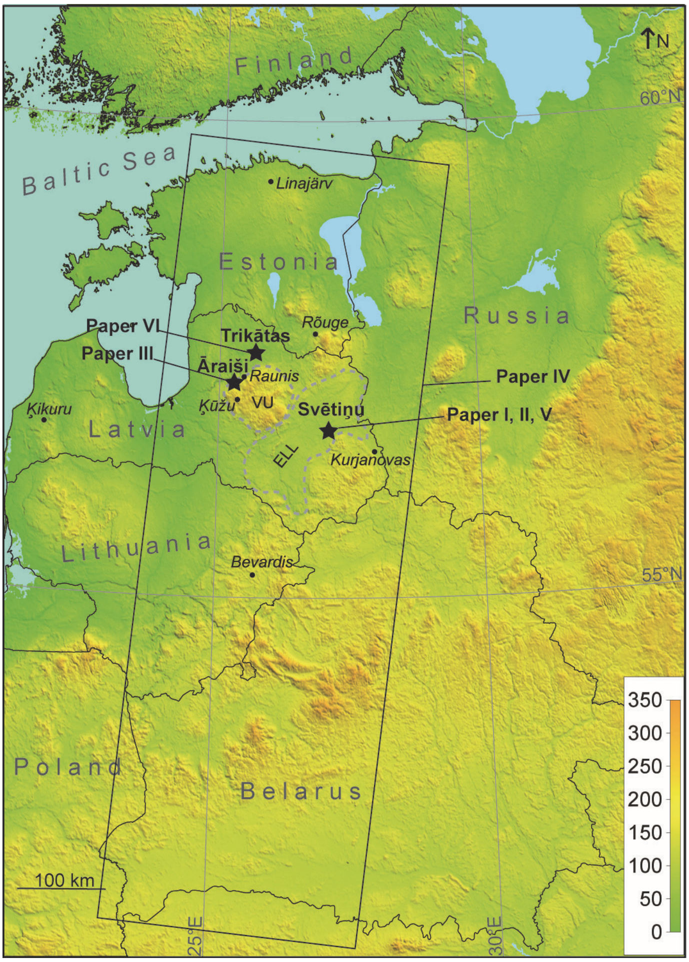

Figure 1. The studied sites are marked by stars and some of the sites discussed in the text are marked by dots. The grey dotted lines indicate the location of the VU – Vidzeme Upland and the ELL – Eastern Latvian Lowland. Study areas or sites related to certain papers are given.

Latvia is rather flat with an average altitude of approximately 90 m a.s.l. The highest point, Gaiziņkalns in the Vidzeme Upland, reaches 312 m a.s.l., but elevations higher than 200 m a.s.l. are restricted to less than 3% of the area (Zelčs and Markots 2004). Although Grewingk (1879) was the first to assume that Pleistocene glaciations in Latvia are of different ages, it was Aleksis Dreimanis who found conclusive evidence for three Pleistocene glaciations in Latvia (Zelčs and Raukas 2011). The present-day topography has largely been formed as a result of the Pleistocene glaciations, particularly the last Weichselian glaciation and the following deglaciation (Zelčs and Markots 2004; Zelčs et al. 2011).

The study area is located in the hemiboreal vegetation zone and is characterised by deciduous-coniferous (mixed) forest. The typical coniferous species are Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*), and the typical deciduous species are birches (*Betula* spp.), alders (*Alnus glutinosa*, *Alnus incana*), mountain elm (*Ulmus glabra*), ash (*Fraxinus excelsior*), lime (*Tilia cordata*) and oak (*Quercus robur*).

The climate in the area is transitional from maritime to continental, therefore the annual frequencies of arctic and sub-polar air masses is fairly high (Draveniece 2009; Avotniece et al. 2010). The mean annual temperature in central Latvia (Riga) from 1851 to 2006 was 6.2 °C, ranging from -2.6 °C (mean December temperature) to 18.0 °C in July (Dauškane 2010). The mean annual precipitation from 1851 to 2006 in Latvia (Riga) was 614 mm (Dauškane et al. 2011).

Lake Lielais Svētiņu (water depth 4 m; 56°46'N; 27°08'E) and Mazais Svētiņu Bog (56°45'N; 27°08'E) are located in the Rēzekne district of eastern Latvia (Fig. 1), in the Eastern Latvian Lowland 13 km east of Lake Lubāns. The bedrock consists of Devonian dolomite covered by Quaternary deposits with a thickness of 5–10 m consisting of sand, silt and clay. Lake Lielais Svētiņu is a drainage lake with an area of 18.8 ha and is located at an elevation of 96.2 m a.s.l. Its catchment (~12 km^2) is predominantly forested but also partly covered by fields. Mazais Svētiņu Bog represents a stand-scale site, and its catchment area is restricted to 20–100 m^2.

Lake Āraiši is located (57°15'N; 25°17'E) in central Latvia (Fig. 1), on the western edge of the Vidzeme Upland, 6 km south of Cēsis at an elevation of 120.2 m a.s.l. The area of the lake is 32.6 ha. It has a flow-through hydrological regime and a mean and maximum depth of 4 and 12.3 m, respectively. The size of the lake's catchment area is ~10 km^2. The geology is Devonian sandstone overlain by 80 m of till.

Lake Trikātas (57°32'N; 25°42'E) is situated in northern Latvia (Fig. 1), in the north Vidzeme lowland 17 km east of Valmiera at an elevation of 50 m a.s.l. The surface area of the lake is 13 ha, and the mean and maximum water depths are 1.8 and 6.5 m, respectively. The lake is located in a 25 m deep valley with an outflow connected with the River Abuls on the western side. The surrounding landscape comprises a mixture of cultivated land and pasture overlaying sandy and podzolic soils (Kasparinskis and Nikodemus 2012). Quaternary glacial till and alluvial deposits in the Trikātas area overlie Devonian sandstone bedrock.

1.2. Methods

The methods that were used are described in separate papers included in the current thesis. The primary study method was analysis of pollen and non-pollen palynomorphs. Samples for pollen analysis (Papers I–III, V–VI) were performed using standard acetolysis procedures (Berglund and Ralska-Jasiewiczowa 1986; Fægri and Iversen 1989). Known quantities of *Lycopodium* spores were added to each sample (except for Mazais Svētiņu Bog) to allow calculation of pollen concentration and PAR (Stockmarr 1971; Chambers et al. 2011). Microscopic charcoal content in the pollen slides was estimated as in Finsinger et al. (2008).

A wide group of other microfossils (van Geel 2001) were recorded alongside pollen and identified using the published literature on non-pollen palynomorphs that was listed in Papers III and V.

Furthermore, a variety of analyses were performed to obtain additional information on related changes of and within a catchment of the studied sites. The procedures and descriptions of the applied methods are given in Papers I–VI. The OM content of the sediment was determined by LOI (Heiri et al. 2001), and the ignition residue was estimated as the MM content of the sediment (Papers I–III, V–VI). MS (Papers I, III, V–VI) showing the minerogenic particles contribution to the sediment was measured with a Bartington MS2E meter (Nowaczyk 2001). Plant macrofossils that provided information on the vegetation growing directly around the sedimentary basin (Birks and Birks 2006; Amon et al. 2014) was applied in Papers I and VI. The degree of decomposition of the Mazais Svētiņu Bog peat was determined to characterise the bog surface wetness (Paper II) (von Post 1924; Stanek and Silc 1977; Malterer et al. 1992). Diatom analysis was carried out to reconstruct past natural and human-induced changes on the lake trophic state (Papers I, III) (Battarbee 2001; Krammer and Lange-Bertalot 1986-1991). To look at the sedimentation history and human impact, a wide range of geochemical elements were analysed by ICP-OES (Paper III) (Holliday and Gartner 2007; Cook et al. 2010; Hutson and Terry 2006). To characterise the climate, pollen-based temperature reconstructions (T_{win} and T_{sum}) were done based on the WA-PLS regression and calibration technique (ter Braak and Juggins 1993) (Papers IV and V). To characterise general trends in changes to terrestrial vegetation, unconstrained ordination of pollen data was used – namely PCA on the covariance matrix of the Hellinger-transformed pollen percentages (Paper III). A study of the associations between the fossil phytoplankton communities and reconstructed environmental proxies RDA (Rao 1973) was performed in Paper V.

To place the palaeobotanical data within a cultural context, the results were presented and discussed in relation to Latvian archaeological and historical periods: Late Paleolithic >8000 BC, Mesolithic 8000–4500 BC, Neolithic 4500–1500 BC, Bronze Age 1500–500 BC, Early Iron Age 500 BC–AD 400, Middle Iron Age AD 400–800, Late Iron Age AD 800–1200, Medieval period AD 1200–1550, Postmedieval period AD 1550–1850 and Modern period AD 1850–present (Vasks et al. 1999; Graudonis 2001; Zagorska 2001). Archaeological and historical periods as well as BC/AD age scale were used when human impact was discussed, but cal BP was used in all other cases throughout the current thesis.

1.2.1. Sediment sampling

Lake sediment samples from Lake Lielais Svētiņu, Lake Araiši and Lake Trikātas were obtained from ice using one-meter long Russian-type corers with diameters of 7.5 and 10-cm. The topmost 0.5 m of unconsolidated sediment were sampled using a Willner-type gravity sampler. Sediment cores were documented and packed into film-wrapped, one-meter plastic PVC semi-tubes. The topmost sediment sequence was sub-sampled into 1-cm slices and put in plastic bags. A 500-cm-long sediment sequence was taken from Mazais Svētiņu Bog using an Ejelkamp peat sampler with a 5-cm diameter and 50-cm length. All of the samples were transported to the laboratory for further analyses (Table 1).

Table 1. The applied analytical methods are expressed by the number of samples that were analysed

Palaeoecological analyses	Lake Lielais Svētiņu	Lake Āraiši	Lake Trikātas	Mazais Svētiņu Bog	Methods described in Papers
AMS ^{14}C dating	12	5	7	-	I, V, VI
Conventional ^{14}C dating	8	12	6	3	II, III, V, VI
SFAP	-	28	-	-	III
Pollen	136	42	36	41	I–III, V, VI
Non-pollen palynomorphs	101	36	33	-	III, V
Plant macrofossils	77	-	65	-	I, VI
Diatoms	28	33	16	-	I, III
Degree of peat decomposition	-	-	-	165	II
LOI	1066	621	199	-	I–III, V, VI
MS	381	621	496	500	I, III, V, VI
ICP-OES	-	57	35	-	III

1.2.2. Dating

For Lake Lielais Svētiņu (Papers I–II, IV and V), twelve AMS ^{14}C dates from terrestrial macrofossils and eight conventional ^{14}C dates from bulk sediment were determined. Macrofossils were radiocarbon-dated using the AMS method in the Poznań Radiocarbon Laboratory (Poz) in Poland, and bulk samples were dated by the conventional liquid scintillation method at the Institute of Geology, Tallinn University of Technology (Tln) in Estonia. In Papers I, II and IV, radiocarbon dates were calibrated using the IntCal09 calibration dataset (Reimer et al. 2004), and an age-depth model was built with an OxCal 4.1 depositional model, including visible sedimentary boundaries (Reimer et al. 2004; Bronk Ramsey 2008). In Paper V, an OxCal 4.1.2 depositional model and the application of the IntCal13 calibration set (Reimer et al. 2013) was used.

For Lake Āraiši (Paper III), the chronology was based on 7 conventional ^{14}C Tln dates from bulk sediment samples, and for the upper sequence the distribution of SFAP was used. The peak in SFAP at depth 35 cm was assigned to AD 1970±10 (Rose 1990;

Heinsalu and Alliksaar 2009). Radiocarbon dates were converted to calendar years using the IntCal13 calibration dataset (Reimer et al. 2013) and the Clam 2.2 programme deposition model (Blaauw 2010), with a 95.4% confidence level.

The chronology of the sediment sequence of Lake Trikātas (Paper VI) was established based on a Bayesian age-depth model constructed from 6 AMS ^{14}C dates. The dated material, all of which was of terrestrial origin, was processed at the Scottish Universities Environmental Research Centre, United Kingdom (GU), and Poznań. In addition seven gyttja bulk materials were dated in Tallinn to estimate the potential hard water effect and dating error offset in comparison to AMS dates. Radiocarbon dates were converted to calendar years using the IntCal13 calibration dataset (Reimer et al. 2013) and Clam 2.2. programme deposition model (Blaauw 2010), with a 95.4% of confidence level.

2. RESULTS

2.1. Lithostratigraphy and chronology

Descriptions of the sediments at the studied sites are given in Table 2. Lake Lielais Svētiņu (Papers I–II, IV and V), Lake Āraiši (Paper III) and Lake Trikātas (Paper VI) comprise mostly gyttja with silts and clay silts at the bottom part of the sequences. The Mazais Svētiņu Bog (Paper II) sequence consists mainly of peat.

Table 2. Description of the sediments at the studied sites

Depth from the water surface, cm	Sediment description
Lake Lielais Svētiņu	
400–1105	Gyttja, brown, homogeneous
1105–1160	Gyttja, silty, greenish brown, homogeneous
1160–1190	Silt, dark gray, with OM
1190–1268	Silt, light gray
1268–1317	Silt, yellowish, with diffuse OM
1317–1332	Clay, distinctly laminated
1332–1498	Silt, gray, increasingly dark-coloured towards the upper limit
1498–1515	Sand, dark-coloured
1515–1535	Sand, beige, compact
Mazais Svētiņu Bog	
0–5	*Sphagnum* peat
5–30	Wood-grass peat
30–155	Sedge peat
155–170	Wood-sedge peat
170–205	Wood-grass peat
205–360	Wood peat
360–375	Sand
375–410	Wood peat
410–420	Sand
420–425	Wood peat
425–435	Sand
435–450	Wood peat
450–500	Till
Lake Āraiši	
1230–1257	Gyttja, silty, black
1257–1263	Gyttja, silty, dark brown
1263–2150	Gyttja, silty, homogeneous, dark brown
2150–2270	Gyttja, silty, light gray-brown
2270–2320	Gyttja, gray brown
2320–2350	Gyttja, brown, dark
2350–2356	Clay, silty, black brown, dark
2356–2377	Clay, silty, gray, light
2377–2379	Clay, silty, dark gray
2379–2400	Clay, silty, gray, dark

2400–2467	Clay, silty, brown gray, dark
2467–2474	Sand with gravel, gray, light
Lake Trikātas	
400–410	Gyttja, silty, calcareous, yellow
410–445	Gyttja, silty, calcareous, black
445–514	Gyttja, silty, calcareous, brown, dark
514–537	Gyttja, silty, calcareous, brown, light
537–575	Gyttja, silty, calcareous, gray brown, light
575–642	Gyttja, silty, calcareous, gray brown, dark
642–663	Gyttja, silty, calcareous, brown, dark
663–800	Gyttja, silty, brown, dark

The results of the radiocarbon dating are summarised in Table 3. The ^{14}C dates for Lake Lielais Svētiņu (Papers I, II), Mazais Svētiņu Bog (Paper II), and part of Lake Āraiši (Paper III) have been published, but Lake Trikātas (Table 3; Paper VI) and part of Lake Āraiši (Table 3) are presented for the first time herein.

Table 3. Radiocarbon dates from the studied sediment sequences

Depth, cm	Lab code	^{14}C date yr BP	Calibrated age, cal BP	Dated material
Lake Lielais Svētiņu				
523	Tln-3167	1848±70	2110–1725	Bulk gyttja
593	Tln-3168	3231±70	3480–3170	Bulk gyttja
673	Tln-3169	4091±70	4680–4420	Bulk gyttja
743	Tln-3170	4701±70	5590–5350	Bulk gyttja
823	Tln-3171	5822±90	6790–6500	Bulk gyttja
893	Tln-3172	6876±90	7840–7590	Bulk gyttja
973	Tln-3173	7974±90	9090–8730	Bulk gyttja
1043	Tln-3174	9169±100	10,300–9900	Bulk gyttja
1157	Poz-30426	10,100±60	11,650–11,590	Wood
1185	Poz-36710	10,270±50	12,140–11,810	Twig
1215	Poz-31768	10,330±50	12,400–12,120	Wood
1261	Poz-31769	10,760±50	12,760–12,560	Twig, bark
1315	Poz-36711	11,460±60	13,400–13,160	Bark
1355	Poz-36712	11,670±60	13,620–13,400	Stem
1365	Poz-36715	11,630±60	13,660–13,460	*Betula nana* leaf, *Potentilla* seed
1400	Poz-36713	11,840±60	13,830–13,640	Twig
1445	Poz-36714	12,410±60	14,240–13,990	Twig, *Betula nana* leaf
1492	Poz-31770	12,380±60	14,400–14,040	Twig, bark
1510	Poz-29298	12,420±60	14,590–14,150	Wooden material
1530	Poz-31771	12,350±60	14,950–14,180	Wooden material
Mazais Svētiņu Bog				
165	Tln-3202	2613±60	2860–2490	Bulk peat
335	Tln-3203	5154±70	6180–5730	Bulk peat
435	Tln-3205	7297±100	8340–7950	Bulk peat
Lake Āraiši				
1300	Poz-53115	510±30	505–555	Bulk gyttja
1373	Tln-3308	684±95	520–785	Bulk gyttja
1423	Tln-3309	943±105	680–1020	Bulk gyttja

1473	Tln-3310	1106±95	900–1260	Bulk gyttja
1523	Tln-3311	1280±110	970–1370	Bulk gyttja
1573	Tln-3316	1365±60	1175–1380	Bulk gyttja
1623	Tln-3317	1636±65	1640–1695	Bulk gyttja
1673	Tln-3318	1843±70	1605–1930	Bulk gyttja
1723	Tln-3312	2163±75	1995–2335	Bulk gyttja
1773	Tln-3313	2487±75	2375–2740	Bulk gyttja
1813	Tln-3314	2667±70	2700–2955	Bulk gyttja
1853	Tln-3315	2951±70	2925–3270	Bulk gyttja
1893	Tln-3319	3311±65	3400–3650	Bulk gyttja
2052	Poz-48431	4410±35	4865–5060	Leaf
2225	Poz-53113	6470±35	7310–7440	Bulk gyttja
2353	Poz-53112	9970±60	11,245–11,640	Bulk gyttja
2397	Poz-53111	12,360±60	14,110–14,750	Wood
Lake Trikātas				
450	GU-27675	1115±35	1090–935	Bulk gyttja (hard water error)
475	GU-27676	1200±35	1190–1050	Bulk gyttja (hard water error)
477	GU-29839	1918±26	1930–1820	*Spergula arvensis* (hard water error)
481.5	GU-29840	158±26	230–165	*Ranunculus* leaf fragments
483	Poz-61639	175±30	225–135	Wood
500	GU-27677	1535±35	1525–1350	Bulk gyttja (hard water error)
525	GU-27678	1735±35	1720–1555	Bulk gyttja (hard water error)
545	Poz-61640	915±30	920–760	*Picea abies* needles, fragment of seed
550	GU-27679	2800±35	2990–2840	Bulk gyttja (hard water error)
575	GU-27680	2840±35	3060–2860	Bulk gyttja (hard water error)
577	Poz-61641	1345±30	1310–1240	*Picea abies* needle fragment
689	Poz-61642	2485±30	2725–2440	Wood
723	Poz-61643	2990±30	3250–3070	Wood

2.2. Palaeobotanical analyses

In the present thesis, the main emphasis is on pollen and non-pollen palynomorphs, therefore a short overview of the results has been given further below. Detailed results of the other methods can be found in Papers I–VI.

During the LG, pollen proportions were dominated by non-arboreal pollen from 14,560 to 13,760 cal BP (GI-1, Bølling) and 12,700–11,650 cal BP (GS-1, Younger Dryas), and arboreal pollen (mainly *Betula* and *Pinus*) dominated from 13,760–12,700 cal BP (GI-1, Allerød) in the area surrounding Lake Lielais Svētiņu (Paper I). Furthermore, corroded and redeposited thermophilous pollen grains were recorded during cooling phases. The Holocene was characterized by mixed conifer forests in the Early Holocene (11,650–8000 cal BP). Within the expansion of thermophilous tree species, a sudden decline of the pollen values of all the broad-leaved taxa occurred at 8200 cal BP. The Mid-Holocene (8000–4000 cal BP) was characterised by the dominance of thermophilous trees species, and the Late Holocene, from 4000 cal BP to the present, (Papers I–II) was dominated by mixed conifer-deciduous forest.

Cereal pollen grains as indications of cultivation show the presence of *Avena*, *Hordeum*, *Triticum* and *Secale cereale* only in the Late Holocene (Papers II–III, VI).

The first cereal grains of *Avena*, *Triticum* and *Hordeum* were recorded from 500 and 100 BC, respectively (Paper VI). Significant intensification of cultivation began in the Late Iron Age and Medieval period, as shown in the results presented in Papers III and VI, and continued to increase, with highest AR occurring from AD 1800–1900.

2.3. Non-pollen palynomorphs analyses

During the LG, the highest AR and percentage values of phytoplankton occurred in GI-1, but overall, the LG was characterised by low phytoplankton AR (Paper V). *Scenedesmus* and *Tetraedron minimum* were the dominant phytoplankton during the LG. The Holocene had major changes in phytoplankton community with a rapid increase in their AR. From 11,650 to 8000 cal BP, *Tetraedron minimum*, *Scenedesmus*, *Botryococcus* and *Glaucospira* were the dominant taxa. Later, between 8000 and 2000 cal BP, cyanobacteria overwhelmed other algae and had their highest AR and percentages (Paper V). A rapid decrease in cyanobacteria and an increase in *Pediastrum*, *Botryococcus* and *Coelastrum* occurred during the last 2000 years.

Lake Āraiši (Paper III) had a low AR of cyanobacteria, *Botryococcus* and *Pediastrum* during the Early Iron Age (AD 1–400). Within fungi, the highest AR of *Kretzschmaria deusta* was recorded. *Sordaria*, *Sporormiella* and *Glomus* spores increased abruptly after AD 750 (Middle Iron Age). The Late Iron Age (AD 800–1200) was characterised by a rapid increase of cyanobacteria from AD 800–1000 and decrease afterwards. An abrupt decrease of *Sordaria* and *Sporormiella*, *Glomus* and other ascospores was recorded at AD 1050. Only *Sporormiella* and *Podospora* had more frequent appearance throughout Historical times (AD 1200–present). *Botryococcus*, *Pediastrum*, *Scenedesmus* and *Tetraedron minimum* had elevated AR from AD 1200–1500.

3. DISCUSSION

3.1. Postglacial environmental and climatic conditions

3.1.1. Lateglacial

Palaeoecological records preserved in sedimentary deposits provide a unique insight into the nature of past ecosystems. Moreover, rapid fluctuations in climate and environmental conditions during the LG make this time period an important focus of studies (Lowe et al. 1999; Heikkilä et al. 2009; Kalm 2012; Amon et al. 2014; Feurdean et al. 2014). Relatively small closed lakes are sensitive to these changes because they integrate sedimentary information of the variations in the lake basin and its catchment. Although studies on the LG in the eastern Baltic area go back almost a century, they focus on ice-recession stages and chronology (Dreimanis 1935, 1947; Zelčs and Markots 2004; Stančikaitė et al. 2008; Koff and Terasmaa 2011; Zelčs et al. 2011; Kalm 2012; Saarse et al. 2012); there is a paucity of studies on climatic and environmental change. Thus, uncertainty remains with respect to the relative timing of environmental changes in relation to climatic fluctuations during the LG.

Radiocarbon dates revealed that the establishment of ice-free ground in the surroundings of Lake Lielais Svētiņu (Paper I) and Lake Āraiši (Table 3) occurred by at least 14,560 and 14,390 cal BP, respectively. These dates are in good agreement with the results of regional studies (Heikkilä and Seppä 2010; Amon et al. 2014; Stančikaitė et al. 2014) and support the idea of relatively rapid ice retreat from the eastern Baltic area. Furthermore, the age obtained from Lake Āraiši is considerably older (14,390 cal BP) in comparison with Lake Ķūžu (12,900 cal BP) (Koff and Terasmaa 2011), which is located only 25 km to south, and with the Raunis site (13,300–13,200 cal BP) (Amon 2012), which is located 10 km to northeast (Fig. 1). Therefore, a complex deglaciation pattern persisted which suggests differences not only across the eastern Baltic but also on a smaller scale restricted to the western parts of the Vidzeme Upland, central Latvia. Complexity is attributed also to the fact that several influencing landscape features, such as the survival of buried blocks of dead ice (Lake Ķūžu) and ice meltwater lakes (Raunis), can occur in a small area. The study by Nartišs (2013) on reconstructions of ice meltwater lakes supports the complexity of the retreat of the Late Weichselian ice sheet margin in central and northern Latvia. Therefore, we can argue that the geomorphological characteristics and landscape were not uniform during the LG.

The complexity of deglaciation process was significantly controlled by the decaying ice sheet, proglacial lakes and mean air temperature throughout the LG, which also influenced the environmental conditions also in other regions in Europe (Birks and Birks 2014; Feurdean et al. 2014). Quantitative pollen based temperature reconstructions indicate that the mean T_{win} was as low as -16.8 °C during GI-1 (14,650–12,850 cal BP) and as low as -17.5 °C during GS-1 (12,850–11,650 cal BP) in Latvia (Paper IV). The highest T_{win} (-16 to -15 °C) was reached between 13,900 and 12,850 cal BP. Regional synthesis from multiple sites within the transect from

Estonia–Latvia–Lithuania–Belarus (Paper IV) revealed that during GI-1, T_{win} was over 10 °C colder than today in Latvia and Estonia and approximately 8 °C colder than today in Belarus. A similar gradient and magnitude of temperature change was also recorded during the GS-1, which suggests latitudinal differences caused by the proximity of the Scandinavian ice sheet. Moreover, the decrease in T_{win} and T_{sum} during GS-1 (12,850–11,650 cal BP) and the increase in MM and fungi *hyphae* indicate that this time was characterised not only by cold climate but also by high soil erosion within the catchment (Papers I, II and V). Paper I highlights a parallel increase in corrosion of pollen grains and redeposition of thermophilous pollen grains, which supports the idea that soil erosion was the main cause of the increase in MM and fungi *hyphae* AR in Lake Lielais Svētiņu during the cold phases of the LG.

3.1.2. The Holocene

The Holocene began with a rapid transition from a cold to a generally warmer time at 11,650 cal BP, when the mean T_{win} rose abruptly by nearly 10 °C in Latvia (Paper IV). The Early Holocene (11,650–8000 cal BP) therefore marks an improvement in the climate and a rise in temperature, which also initiated the change in the sediment type. The OM rich gyttja was sedimented instead of silts and clays (Paper II). However, there was a delay in the rise of T_{win}, and the temperatures reached modern values at 9000 cal BP in Latvia, in comparison to the southern parts of Belarus, where modern values were reached 1000 years earlier (Paper IV).

The cold event approximately 8200 cal BP (8.2 ka event) led to a drop in T_{win} by 2–3 °C and an associated decrease in the OM of the Lake Lielais Svētiņu sediments and demonstrated a strong environmental disturbance for nearly 700 years (Paper II, IV, V). Moreover, Hede et al. (2010) point to strong erosional export of nutrients to Højby Sø in Denmark from 8500–7900 cal BP. Therefore, parallel trajectories with small shifts in timing and duration are indicated for both areas. The 8.2 ka event was the most extreme cold event after the Younger Dryas in the area (Veski et al. 2004). The regional cooling has been generally attributed to a temporary slow-down of the North Atlantic thermohaline ocean conveyor (Dawson et al. 2011), which was caused by one of the largest Lake Agassiz–Ojibway freshwater outbursts into the Hudson Bay approximately 8500 cal BP (Barber et al. 1999; Seppä et al. 2007; Daley et al. 2011). Climate model simulations show that the timing and duration of the 8.2 ka event varies geographically (Seppä et al. 2007; Wiersma et al. 2008). Duration of the 8.2 ka event impact on a variety of ecosystems in the northern hemisphere was ca. 300 years according to the climate model simulations, but proxy data from coeval stalagmites suggest that the climate anomaly lasted about ca. 100 years in Austria, and by the high-resolution multi-proxy varved study ca. 150 years in central Finland, and within the ca. 200 yr by $\delta^{18}O$ in southern Estonia (Veski et al. 2004; Ojala et al. 2008; Wiersma et al. 2008; Boch et al. 2009). The 8.2 ka event brought generally cold conditions to broad northern hemisphere regions, especially in the wintertime, when the climate was dominated by blocking high-pressure circulation, giving rise to cold and dry conditions, but greater summer precipitation and elevated lake levels (Alley and

Ágústsdóttir 2005; Hammarlund et al. 2005). Several other effects of the those circumstances might be linked to the 8.2 ka event, such as sea-level changes, lower sea-surface temperatures in the North Atlantic Ocean, changes in precipitation net, freshening of ocean water, lower methane concentration in the atmosphere, ice rafting and "*Finse event*" glacier fluctuations (Hammarlund et al. 2005; Seppä et al. 2007; Wanner et al. 2011; Quillmann et al. 2012). All of these factors could have affected the climatic and environmental conditions in the eastern Baltic. Despite fine differences in the length and timing of the delay in the impact of cooling at different localities, we can argue that the 8.2 ka event was very rapid and remarkable in Latvia as well.

Warm (~3.5 °C above the modern temperature) (Paper V), dry and overall stable climate conditions with low water levels in lakes typically persisted during the HTM from 8000 to 4000 cal BP (Hammarlund et al. 2003; Sohar and Kalm 2008; Seppä et al. 2009; Heikkilä and Seppä 2010; Muschitiello et al. 2013). The high peat decomposition at Mazais Svētiņu Bog (Paper II) and the domination of dry and warm environmental conditions in Latvia support this estimation. Berbeco et al. (2012) showed that if soil and bog surfaces become warmer and drier, it increases decomposition of fine, woody debris and could induce peat decomposition in bogs as well. In addition, the study of Renssen et al. (2012) indicated that the HTM was delayed by 2000–3000 years over Europe although the highest insolation occurred from 11,000 to 5000 cal BP, mainly as an effect of the remnants of the Early Holocene Laurentide ice sheet in North America.

The Late Holocene since 4000 cal BP was characterised by a gradual decrease in air temperature to the present level, and a decrease in the peat decomposition rate since 4500 cal BP may indicate wetter conditions in Latvia (Papers II and V). This change in environmental conditions matches the Late Holocene cooler (Seppä and Poska 2004) and wetter (Hammarlund et al. 2003) phase previously shown at a regional level.

3.2. Postglacial vegetation history

3.2.1. Lateglacial

To-date, the Lake Lielais Svētiņu sediment sequence represents the longest and most complete record of vegetation history since the GI-1 (14,500 cal BP) in the eastern Baltic (Papers I and II). Therefore, the record holds great potential for understanding vegetation dynamics since the first appearance of ice-free terrestrial ground and for improving our knowledge on taxa migration routes and vegetation succession throughout the postglacial time. Moreover, the comparison of two adjacent sites representing local and regional vegetation history (Paper II) may reflect differences between local and regional changes in vegetation dynamics.

After the ice retreated from eastern Latvia not later than 14,560 cal BP (Paper I), environmental conditions become suitable for the establishment of pioneer vegetation (Paper I). At first the plant cover was scarce and characterised as treeless tundra, but with the increase of air temperature at GI-1 between 13,900 and 12,850 cal BP the landscape was predominately *Betula*-*Pinus* forest tundra. A comparable site, Lake Kurjanovas (Heikkilä et al. 2009), situated 60 km to the east of Lake Lielais Svētiņu

(Fig. 1) indicates that the *Betula*-*Pinus* forest persisted during the warmest phase of the LG.

The most prominent 1000-year cooling event (GS-1) in the LG remarkably affected the vegetation composition in the northern hemisphere as well as in Latvia. Forest species declined abruptly, and the landscape was altered to treeless shrub tundra again (Paper I). Although harsh conditions prevailed throughout the GS-1 *Picea* and *Pinus* survived as suggested by stomatal finds, which might support the idea that eastern Latvia was close to the LG *Picea* and *Pinus* refugium (Huntley 1990; Giesecke and Bennett 2004).

3.2.2. The Holocene

The start of Holocene at 11,650 cal BP (Lowe et al. 2008) was marked by changes in climate and vegetation. Plant macrofossil data confirm the presence of mixed conifer forests (Paper I). In addition, the temperature increase (Papers IV and V) controlled the duration of the growing season, where shorter growing periods favoured conifers over other species in the same overall climate and on similar soils during the Early Holocene (Paper II) (Ellenberg 2009).

The pattern of changes in the forest composition suggests that the dominance of conifers and *Betula* started to weaken at the end of the Early Holocene and later were suppressed by the thermophilous tree species. A similar pattern has been reported in eastern Lithuania (Gaidamavičius et al. 2011) and in northern Belarus (Novik et al. 2010). In addition, the comparison of 7 main tree species within different pollen source areas of local and regional sites (Fig. 2; Paper II) suggests that during the Early Holocene *Picea* locally was replaced by *Betula* as the dominant tree species. Further dominance of *Betula* was suppressed by other thermophilous tree species as a result of the increase in air temperature (Paper V), which is one of the main limiting factors behind tree species competition and coexistence.

Within the expansion of thermophilous tree species, a sudden decline of the pollen values of all the broad-leaved taxa occurred (Paper II), which is a reflection of the 8.2 ka event. The vegetation response to the 8.2 ka event in the area surrounding Lake Lielais Svētiņu was approximately 200 years long, consistence with the data of Heikkilä and Seppä (2010) on Lake Kurjanovas. In addition, Seppä et al. (2007) showed that the vegetation in the Baltic region responded more sensitively to the cooling event than the vegetation at high latitudes. This contrast is attributed to the fact that in the sub-arctic area the vegetation was still dormant and lakes had prolonged ice-cover.

Due to the delay of the HTM in Europe (Renssen et al. 2012), the highest air temperatures in the Holocene occurred from 7500 to 5000 cal BP (Paper V), and eventually this time period was the height of the thermophilous forest expansion (Fig. 2). In addition, the abundance of *Quercus* at local site Mazais Svētiņu Bog suggests

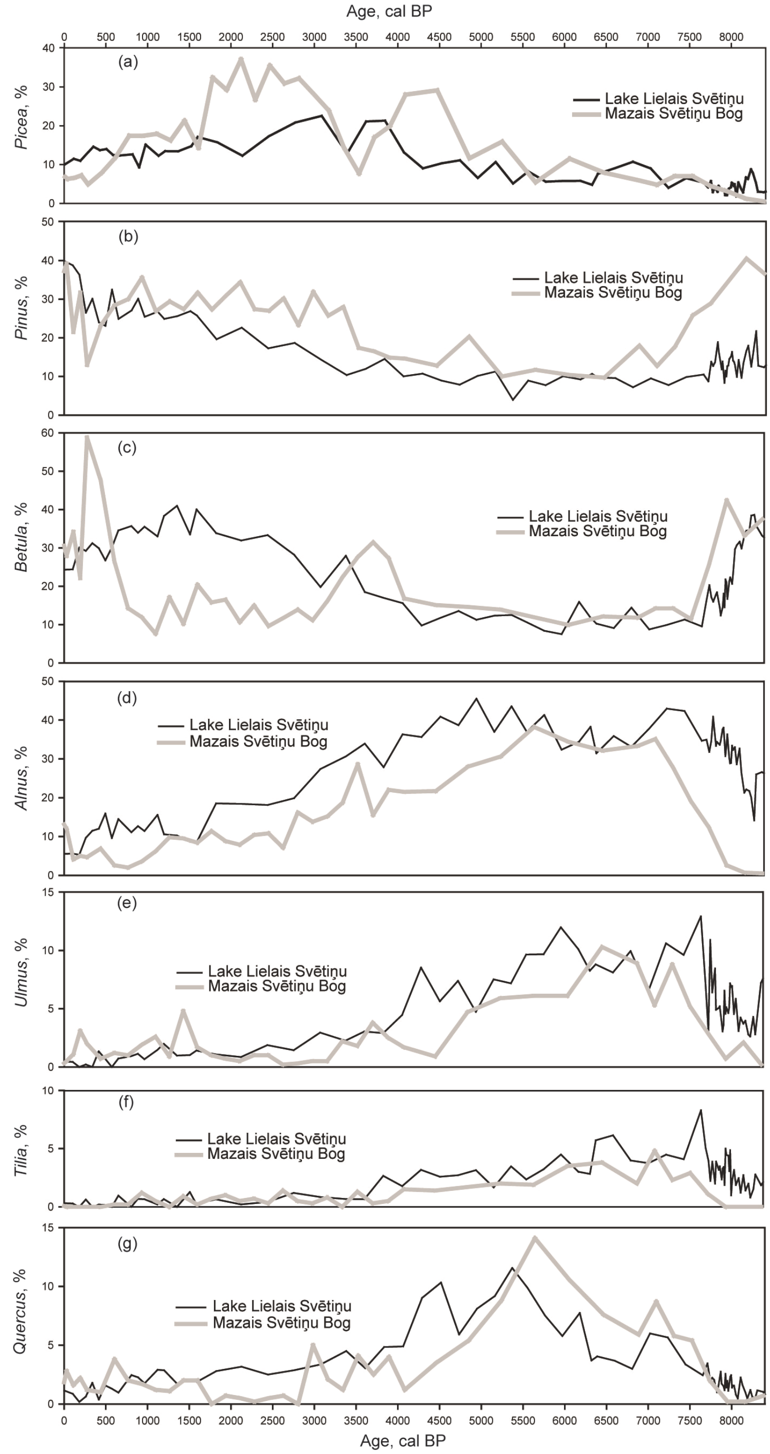

Figure 2. Main tree pollen comparison of Lake Lielais Svētiņu (black solid line) and Mazais Svētiņu Bog (grey solid line): (a) *Picea*; (b) *Pinus*; (c) *Betula*; (d) *Alnus*; (e) *Ulmus*; (f) *Tilia*; (g) *Quercus*.

strictly local changes in the forest composition and availability of light. Although at the stand level *Quercus* can persist for multiple generations under a closed canopy, it has a wide-spreading crown and is thus a relatively light-demanding species that regenerates poorly in such conditions (Lindbladh and Foster 2010; Ikauniece et al. 2012). Values of *Quercus*, *Ulmus* and *Tilia* were consistently comparable to those at Lake Lielais Svētiņu (Fig. 2) and showed no local *vs*. regional differences, suggesting that the regional and local sites contained uniform shares of thermophilous trees.

The lower local abundance of *Betula* suggests regional pollen loading and regional transport at Lake Lielais Svētiņu during the Late Holocene (Dąbrowska 2008; Veriankaitė et al. 2010; Piotrowska and Kubik-Komar 2012). At the same time *Picea* at the local (Mazais Svētiņu Bog) and regional (Lake Lielais Svētiņu) sites (Fig. 2) show similar patterns with maximum populations between 4500 and 2000 cal BP and a decline afterwards. The local fluctuations of *Betula* and *Picea* might suggest not only changes in air temperature but also in humidity and water table around the lake, which can be supported by the variation in peat decomposition rate (Paper II). Moreover, the synchronicity of the increase and decrease of *Picea* is also supported by other regional studies by Heikkilä and Seppä (2010) in Lake Kurjanovas in Latvia, by Koff and Kangur (2003) from the small kettlehole and Lake Linajärv sediments in Estonia and by Gaidamavičius et al. (2011) *via* macrofossil evidence in Lake Bevardis in Lithuania (Fig. 1). Interestingly, a study on small hollows in northwestern Russia by Kuosmanen et al. (2014) presented similar evidence and they discussed that this was a large-scale phenomenon in northern Europe that was not caused by human influence, but was rather due to a regional climate change toward less continental, milder winters and drier summers, which are less favourable for *Picea*.

3.3. Postglacial phytoplankton responses to environmental and climatic changes

Phytoplankton species are the primary producers of biomass in lakes, and they play an important role in the variety of food-web structures. Therefore, any shift in their diversity and production has an impact on other aquatic life forms. The vegetation in surroundings of Lake Lielais Svētiņu has shown responses to climatic change that has transformed the landscape and environmental conditions. Air temperature can also affect lake water temperature, which has proven to be even stronger in lakes at lower altitudes (Gallina et al. 2013), as at Lake Lielais Svētiņu. To see the possible long-term impact of abiotic processes on the aquatic ecosystem, the current thesis presents one of the first attempts to investigate the influence of key environmental factors on the variability of phytoplankton (excluding diatoms) over the last 14,500 years (Paper V).

An improving climate due to increasing air temperature during the GI-1 not only promoted development of terrestrial vegetation in the surroundings of Lake Lielais Svētiņu but also led to increased aquatic productivity. The warming climate, following a decrease in landscape openness and an increase in OM AR, could have been one of the main factors behind the prevalence of *Botryococcus*, *Tetraedron minimum*, *Scenedesmus* and *Pediastrum* among the phytoplankton species (Paper V). The appearance of *Pediastrum* in LG sediments had been previously reported by Sarmaja-

Korjonen et al. (2006) at the classic Bølling Sø site in Denmark. In addition, our results reveal that *Scenedesmus* is positively correlated (0.74) with T_{sum}, which is in accordance with the study of Wacnik (2009). Chlorophyta dynamics follow the same pattern as the improvement in climate and thus directly reflect the impact of climate on the aquatic environment during the LG (Fig. 3; Paper V).

The highest AR and diversity of phytoplankton was reached during the Early Holocene, suggesting environmental heterogeneity within a warming climate envelope. Chlorophyta dominated within phytoplankton. According to the RDA results, water tolerance – indicating moist and unstable soil conditions in the surroundings of the lake – was positively associated with chlorophyta, as *Tetraedron minimum*, *Scenedesmus* and *Pediastrum* (Fig. 3).

Chlorophyta strongly responded to climate disruption at the 8.2 ka event (Fig. 4). Most probably, increased MM in the lake sediments between 8500 and 7900 cal BP accelerated nutrient input into the lake water column that led to rapid increases in chlorophyta AR. The study of Hede et al. (2010) on the evidence of the 8.2 ka event in Lake Højby Sø revealed that the alteration of the terrestrial environment from 8500 to 7900 cal BP resulted in a major change in aquatic ecosystem with nutrient enrichment of the lake and enhanced productivity. These results support our data on the simultaneous timing and effect of the 8.2 ka event on aquatic ecosystems in Latvia.

An abundance of chlorophyta *Coelastrum reticulatum* and *C. polychordum* during the 8.2 ka event was unlikely (Paper V) because these species are thermophilous and are related to warm climatic conditions and anthropogenic eutrophication, as described by Jankovská and Komárek (2000). In our case, we can rule out human-induced eutrophication in the Early Holocene because human impact in the surroundings of Lake Lielais Svētiņu is recorded relatively late, and the lake preserved natural conditions until 1500 cal BP (Paper II). Previously Makohonienko (2000) recorded a rapid increase in *Coelastrum* approximately at the same time in Lake Świętokrzyskie in Poland, and as with our results the increase was not connected with human activities in the vicinity. In addition, *C. reticulatum* already has been recorded in LG in Lake Miłkowskie, Poland (Wacnik 2009) and in Lake Ķikuru (Fig. 1) approximately 8000 cal BP, and in Lake Āraiši in the LG (western and central Latvia, respectively). Due to their characteristic fossil features and specific abundance conditions, *C. reticulatum* and *C. polychordum* appear to be reliable species for characterising the 8.2 ka event or increased nutrient episodes in non-pollen palynomorphs studies on lacustrine sediments in the future.

During the Holocene, absence and dominance of cyanobacteria was strongly related to climate driven increases of T_{sum} and OM, but negatively related to landscape openness that led to the suppressing of chlorophyta (Paper V). Paerl and Huisman (2008) noted that rising temperatures favour the abundance of cyanobacteria, giving them a competitive advantage at elevated temperatures compared to other phytoplankton. The dominance of cyanobacteria in phytoplankton biomass has been shown to lead to a progressive loss of phytoplankton diversity in temperate lakes (Elliott et al. 2006). Cyanobacteria were overwhelming dominant throughout the HTM, with the highest AR between 5000 and 2000 cal BP (Fig. 4). Our results therefore agree with various climate change modelling scenarios that predict that if aquatic systems experience increases in temperature, cyanobacteria will be favoured over other

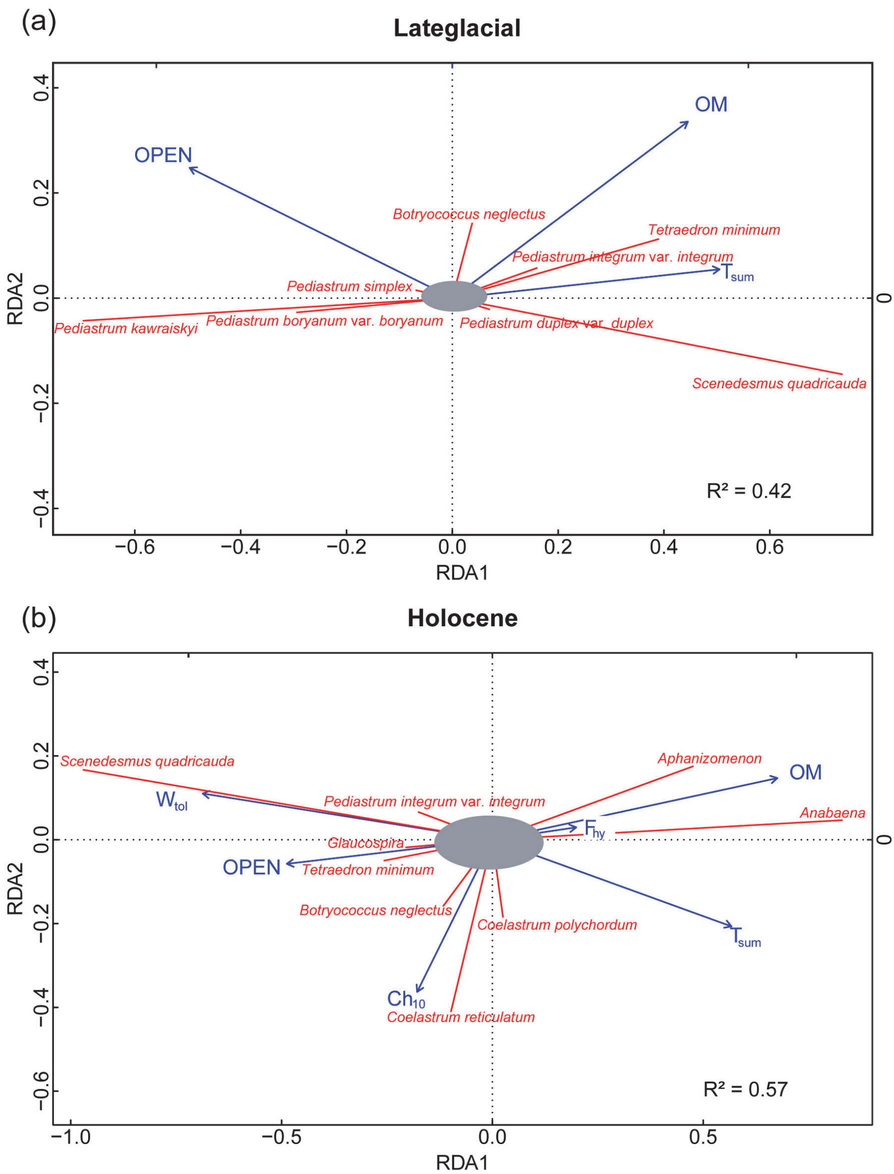

Figure 3. Results of RDA showing the associations between the fossil phytoplankton communities and reconstructed environmental proxies (OPEN – landscape openness; OM; T_{sum}; Ch10 – charcoal >10 *µm*; W_{tol} – waterlogging tolerance; F_{hy} – fungi *hyphae*) in (a) LG and (b) Holocene. Phytoplankton names that are not displayed on the plot were located in the grey elongated area (*Anabaena*, *Aphanizomenon*, *Rivularia*, *Gloeotrichia pisum*, *G. natans*, *Tetraedron minimum*, *Scenedesmus arcuatus*, *Acutodesmus obliquus*, *Desmodesmus opoliensis*, *Botryococcus neglectus*, *B. pila*, *B. braunii*, *Chlamydomonas*, *Pediastrum boryanum* var. *forcipatum*, *P. boryanum* var. *cornutum*, *P. boryanum* var. *longicorne*, *P. boryanum* var. *pseudoglabrum*, *P. boryanum* var. *brevicorne*, *P. orientale*, *P. tetras*, *P. angulosum* var. *coronatum*, *P. angulosum* var. *angulosum*, *P. argentiniense* type, *P. privum*, *Staurastrum gracile*).

phytoplankton (Brookes and Carey 2011; De Senerpont Domis et al. 2013). Climatic and environmental change could be responsible for the increase of cyanobacteria AR, as it suggests a rise in MM (increased nutrients) and a decrease in temperature in the transition from HTM to the Late Holocene (Fig. 3, 4; Paper V). The abundance of cyanobacteria increases with increasing nutrient input and eutrophication in lakes (Ferber et al. 2004). Elliott (2012) showed that the more nutrient rich the lake is, the greater the response of cyanobacteria populations will be. Elevated temperature and nutrient loading decreased approximately 2000 cal BP and thus reduced the dominance of cyanobacteria. This leads to a concurrence with the idea (Elliott et al. 2006; Brooks and Carey 2011; Pätynen et al. 2014) that high nutrient loads and turbidity were more important for the dynamics of cyanobacteria than the increase in temperature alone. The possible cause of the peak of cyanobacteria approximately 1000 cal BP can be attributed to the climate anomaly between ca. 900 and 1350 AD (Graham et al. 2010), and similar abundances also have been recorded in Lake Āraiši (Paper III).

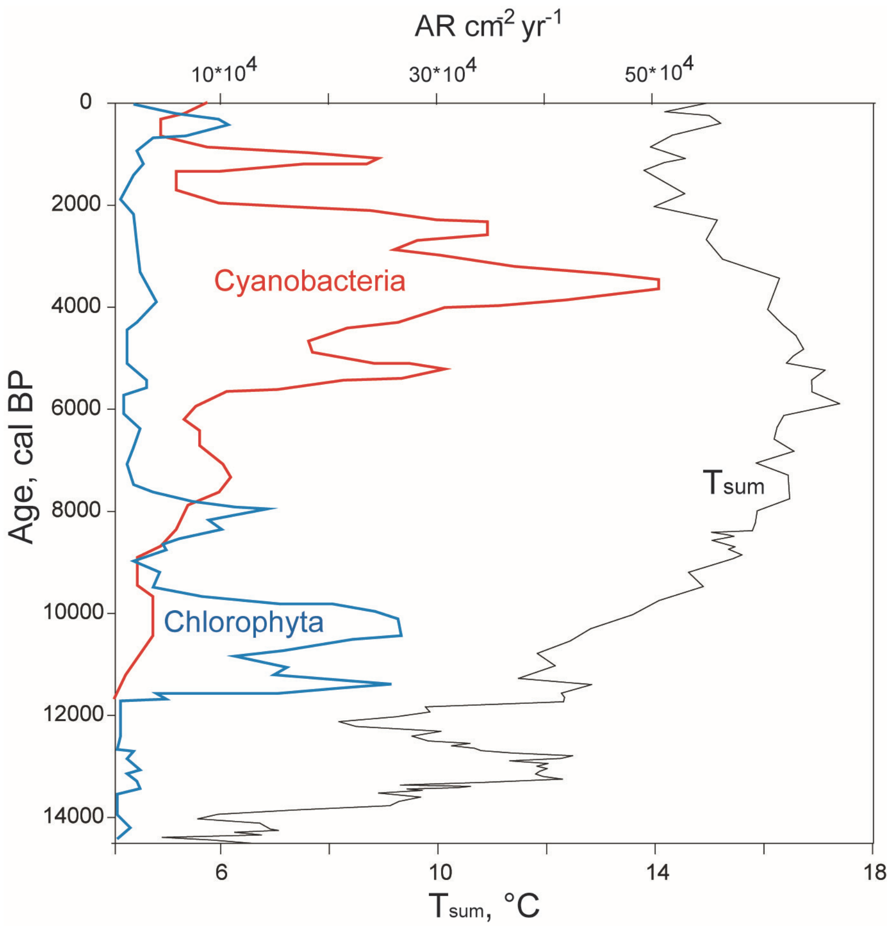

Figure 4. Comparison of the cyanobacteria, chlorophyta and T_{sum} plotted against time.

Despite the great number of algal pigment studies (e.g., Hede et al. 2010), our study shows that higher taxonomic resolution of fossil phytoplankton recovered alongside pollen analysis holds great potential to improve our knowledge on specific algae requirements, responses to stress factors, and co-occurrences of some species, and might be integrated in future non-pollen palynomorphs, ecological and palaeoecological studies.

3.4. Human impact

Mesolithic hunter-gatherers in the Baltic region preferred to settle around larger lakes, rivers and sea coasts; thus their economic system was constrained by the limits of nature, which left little margin for demographic growth (Kuneš et al. 2008; Bocquet-Appel 2011). Climate alteration from warm and dry in the Middle Holocene to wetter and cooler in the Late Holocene (Paper V) favoured a forest ecosystem change from mixed temperate forests to conifer-dominated boreal forests (Paper II), which affected food availability (Tallavaara and Seppä 2011). At the same time the so-called Neolithic transition (Bocquet-Appel 2011; Zimmermann 2012) marked a shift in human history in the eastern Baltic (Bērziņš 2008). The transition was a long and complex process of the acquisition of social behaviours connected to sedentary settlements, development of new economic strategies (e.g., animal and plant domestication) and technical innovations (e.g., pottery, polished stone tools) (Leonardi et al. 2012). The beginning of the Neolithic witnessed a rapid rise in population (Shennan et al. 2007), while specifically hunter-gatherer populations declined (Tallavaara and Seppä 2011). The transition towards an agrarian way of life probably happened during a complex and continuous process of migration, integration and gradual assimilation between pioneering farmers and local hunter-gatherers (Sørensen and Karg 2014). Differential land access in prehistoric Europe within a varying admixture of incoming farmers and local hunter-gatherers had an important impact on the modern European gene pool as well (Bentley 2012; Pinhasi et al. 2012).

Although Latvia has been inhabited by humans since the Paleolithic (Loze 1972, 1997, 2003; Levkovskaya 1987; Vasks et al. 1999; Ozola et al. 2010; Meadows et al. 2014a, 2014b), the dense forests and wetlands, especially in the Lake Lielais Svētiņu area, were inappropriate for farming settlements at first. The continuous presence of forests in the vicinity of Lake Lielais Svētiņu since the establishment of the terrestrial vegetation up to the present verify that this boggy area was not a suitable location for the human settlement or activities before 1500 cal BP (Paper II).

Palaeovegetation records from Lake Trikātas in northern Latvia (Paper VI) also indicate a heavily wooded landscape until 500 BC, when the first traces of the continuous record of cereal pollen indicate the establishment of agricultural practices (Fig. 5). In comparison, a continuous record of cereal pollen grains at Lake Āraiši, central Latvia, is present from AD 400 (Fig. 5), and at Lake Lielais Svētiņu, eastern Latvia, from AD 1300. These results indicate a variation in agricultural practices within and between the Baltic region, wherein at least a 4000 year cultivation history is observed close to settlement centres and much later in peripheral areas (Vasks et al. 1999; Kalnina et al. 2004; Poska et al. 2004; Heikkilä and Seppä 2010; Heinsalu and

Veski 2010; Puusepp and Kangur 2010; Reitalu et al. 2013). Crop cultivation was introduced in Latvia simultaneously with Estonia approximately 4000 BC (Lang 1999; Vasks et al. 1999). The first traces of crop cultivation appear in the Neolithic in the coastal area of western Latvia (Bērziņš 2008) and in the inland area at large lakes in eastern and northern Latvia (Vasks et al. 1999; Kalnina et al. 2004; Ozola et al. 2010).

The clearance of woodland for agricultural purposes, pasture and meadows is most probably reflected as a decline in *Alnus* at Lake Āraiši (Paper III). Saarse et al. (2010) showed that the decline in *Alnus* observed during the Iron Age can be associated with human impact linked to the intensification of cultivation in the eastern Baltic area. The appearance of cereal pollen and declining *Alnus* values in the Lake Āraiši sediments is accompanied by pollen of ruderal habitats, coprophilous fungi and microcharcoal and is strongly indicative of increasing human activities around the lake. A contrary finding was demonstrated by Reitalu et al. (2013), where *Alnus* was positively associated with landscape openness. Černý and Strnadová (2010) reported that lethal root and collar rot disease of *Phytophthora* has rapidly spread hundreds of kilometres and caused considerable losses of *Alnus* since 2000 throughout the Czech Republic. Recorded occurrences of the disease were clearly restricted to bankside *Alnus* stands, carrs, mixed *Fraxinus*-*Alnus* stands and *Alnus* stands in periodically flooded alluvial plains. On the other hand, the study by Pisetta et al. (2012) on *Alnus* decline in the Italian Alps demonstrated that climate change may reduce *Alnus* vigour and allow fungi/parasites to cause decline. At the same time Pisetta et al. (2012) also reported that populations of *Alnus* have been rapidly declining in the Alps since the 1990s. Thus it cannot be excluded that the rapid and widespread *Alnus* decline event was related to climate change and that the spread of lethal root and collar rot had occurred previously. A similar synchronous pattern of *Alnus* decline shown by Saarse et al. (2010) within the time span from AD 300–1300 in Estonia also has been recorded in Latvia from AD 400–700 at Lake Āraiši (Paper III), AD 700–900 at Lake Trikātas (Paper VI), AD 300–800 at Lake Lielais Svētiņu (Paper II), AD 700–1400 at Mazais Svētiņu Bog (Paper II), and AD 400–1000 at Lake Ķūžu (Kangur et al. 2009).

The most significant changes in vegetation and environment during the last 2000 years occurred in Late Iron Age (Paper III) and Medieval period (Fig. 5a; Paper VI). The case study of Lake Āraiši (Paper III) demonstrated that there was intensive land-use since AD 780, which was associated by the establishment of a lake-dwelling. The immediate surroundings of the lake were cleared for agriculture and an open landscape was established.

An abrupt rise in the AR of cereal pollen grains (Fig. 5) supports rapid human-induced landscape openness. Based on the estimation of cereal pollen AR (Paper III), we can conclude that there have been cereal fields within a 2 km radius of Lake Āraiši since AD 750. The magnitude of agricultural practice was variable by location (Fig. 5). For example, although cereal cultivation has been practiced at Lake Trikātas since 500 BC (Fig. 5), an increase in cultivation occurred from AD 1200. This increase was accompanied by higher charcoal frequencies and declines in the surrounding woodland at AD 1200 and suggests a causal link between intensifying land-use and the conquest of Latvia by the Order of the Sword Brothers (Paper VI). The cultivation during the

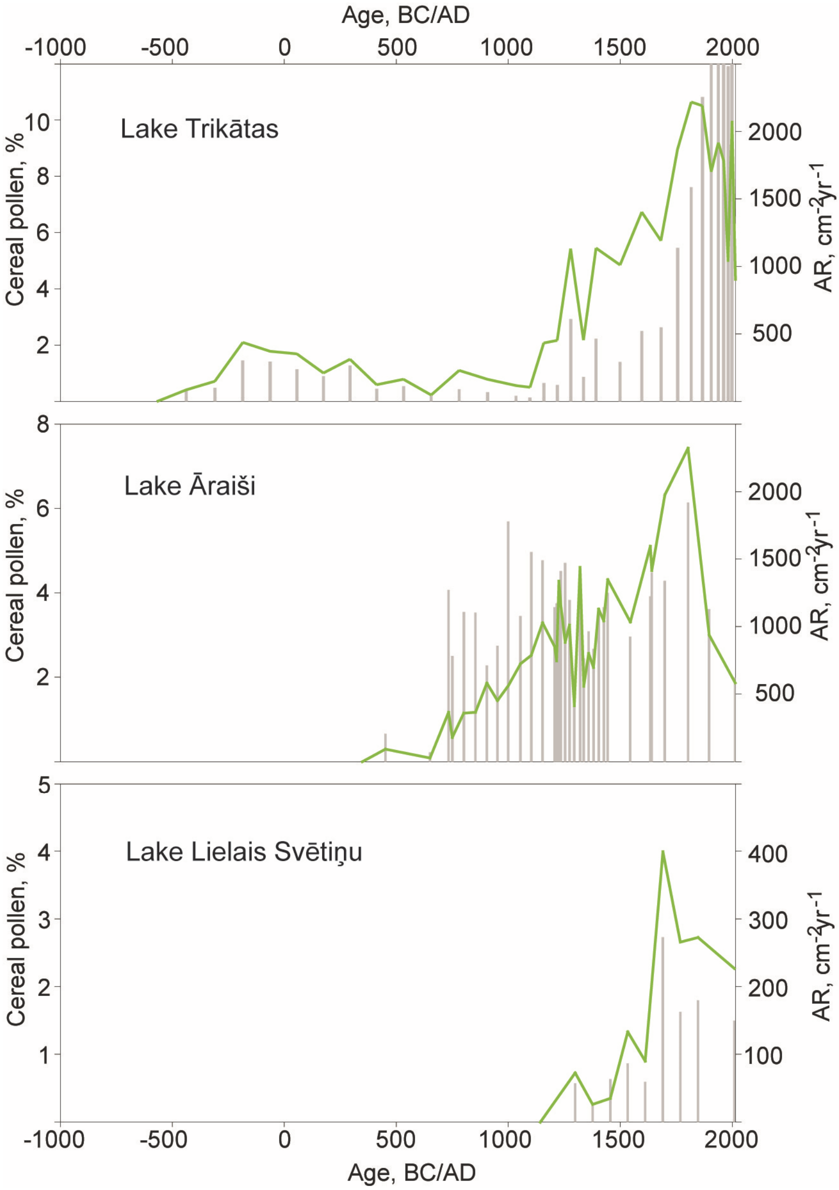

Figure 5. Distribution of pollen cereals in Lake Trikātas, Lake Āraiši and Lake Lielais Svētiņu. Green solid line – percentages (%) of cereal pollen grains; grey vertical posts – AR of cereal grains $cm^{-2}yr^{-1}$.

13th century at Lake Trikātas differs from other records in the region that generally show increases in cereal cultivation a century after the crusades. The study of Veski et al. (2005) at Lake Rõuge Tõugjärv (southern Estonia) showed agricultural activity from AD 1350. Data from Lake Lielais Svētiņu (Fig. 5) and also from peatlands around Cēsis (central Latvia) show a similar pattern of agricultural intensification from the mid-14th century and later (Brown and Pluskowski 2014). Moreover, Lake Āraiši showed a decline in cereal cultivation from the start of the Medieval period, which only again increased during the 14th century (Fig. 5). We can argue that the crusades and conquest of former tribal lands was not accompanied by significant impacts on rural landscapes in Livonia, contrary to Prussia (present-day north-east Poland). Meanwhile, Lake Trikātas demonstrates significant woodland clearance and intensified land use from the early 13th century, immediately following the crusades.

Intensification of land-use, crop cultivation and possibly more open landscape reached its peak during the Manor time (AD 1750–1900) in northern and central Latvia (Fig. 5; Paper III, VI). These results correspond well to the study of Lake Rõuge Tõugjärv in southern Estonia (Veski et al. 2005) that showed a pattern of extensive farming, where the growth in population was compensated by the increasingly large areas of land placed under cultivation. This pattern prevailed until the 1850's, when cereal cultivation shifted from extensive to intensive farming with more effective use of the existing land.

CONCLUSIONS

The thesis discusses postglacial environmental and climatic successions, vegetation dynamics and human impact in Latvia over the last 14,560 years. By taking a long term and multi-proxy approach with pollen and non-pollen palynomorphs as the main study methods, the new results of this thesis allow the new data to be placed in a broader environmental, cultural and historical context within the eastern Baltic region. The main results of the current work can be summarized as follows:

- New radiocarbon dates support the relatively rapid retreat of ice and establishment of ice-free ground in eastern and central Latvia;
- A complex deglaciation pattern persisted in a smaller area; therefore, the geomorphological characteristic and landscape were not uniform most probably across Latvia during the LG;
- The T_{win} was more than 10 °C colder than today in Latvia and Estonia and 8 °C colder than today in Belarus during GI-1 between 14,650 and 12,850 cal BP (Bølling-Allerød);
- T_{win} in southern Belarus reached modern values at 10,000 cal BP, ca. 1000 years earlier than in Latvia and Estonia where it reached modern values at 9000 cal BP;
- During the 8.2 ka cold event, T_{win} lowered by 2–3 °C, which caused an environmental disturbance for ca. 700 years and altered vegetation for ca. 200 years in eastern Latvia;
- The high peat decomposition in the Mazais Svētiņu Bog and 3 °C above the modern temperature during the HTM support the dominance of dry and warm environmental conditions, whereas cooler and wetter conditions were characteristic to the Late Holocene in Latvia;
- The first pioneer vegetation was established and a treeless tundra has existed in Latvia since ca. 14,560 cal BP;
- between 13,900 and 12,850 cal BP the landscape was predominately characterised as *Betula-Pinus* forest tundra;
- Survival of *Picea* and *Pinus* in eastern Latvia throughout GS-1 (Younger Dryas) might support the proximity to the LG *Picea* and *Pinus* refugium area;
- Mixed conifer forest characterized the landscape of the Early Holocene;
- Thermophilous forest expansion reached its height during the HTM and decreased in the Late Holocene;
- The lower local abundance of *Betula* suggests regional pollen loading and regional transport at Lake Lielais Svētiņu during the Late Holocene;
- Maximum values of *Picea* were reached between 4500 and 2000 cal BP and declined afterwards, which might support the occurrence of a large-scale phenomenon in northern Europe caused by a climate change toward milder winter and drier summers;
- Variability in air temperature, humidity and water table changes were the main influencing factors of differences on local and regional vegetation dynamics;

- Phytoplankton dynamics followed the same pattern as increased temperatures led to improving climate during the LG;
- The highest AR and diversity of phytoplankton was reached during the Early Holocene, suggesting environmental diversity within a warming climate envelope;
- Chlorophyta demonstrated a strong reaction to the climate disruption at the 8.2 ka cold event, which support the simultaneous timing and effect of this event to aquatic ecosystems;
- *Coelastrum reticulatum* and *C. polychordum* appear to be reliable species for characterising the 8.2 ka cold event;
- Climate drove increases of T_{sum} and OM, but negative landscape openness led to the dominance of cyanobacteria over chlorophyta during the HTM;
- High nutrient loads and turbidity, not increased temperature alone, promoted an increase in AR of cyanobacteria;
- Continuous agricultural practices were established from 500 BC and AD 400 in northern and central Latvia, respectively;
- Establishment of intensive land-use and crop cultivation occurred from AD 780 in central Latvia, AD 1200 in northern Latvia and AD 1300 in eastern Latvia;
- The most significant human-induced changes in vegetation and environment during the last 2000 years occurred in the Late Iron Age and Medieval period;
- Significantly intensified land-use from the early 13th century immediately following the crusades is exceptionally demonstrated at Lake Trikātas;
- Overall the crusades and the conquest of former tribal lands was not accompanied by significant impacts on rural landscapes in Livonia (present-day territory of Latvia and Estonia), and the form and type of agriculture and land-use continued much as it had during the preceding Late Iron Age;
- The height of agricultural land-use in Latvia was reached from AD 1800–1900.

ABSTRACT

This thesis evaluates and presents the postglacial environmental change, vegetation dynamics and human-induced impact in Latvia, in the eastern Baltic area, during the postglacial time over 14,560 cal BP. In addition, a novel approach of non-pollen palynomorphs was applied to explore phytoplankton responses to environmental and climatic changes. Lacustrine sediment cores from three lakes (Lake Lielais Svētiņu, Lake Āraiši, Lake Trikātas) and one peat sequence (Mazais Svētiņu Bog) were sampled in Latvia. The chronology of sediment sequences was based on conventional and AMS ^{14}C dates and spheroidal fly ash particles. A multi-proxy approach was applied in all studies, but analyses of pollen and non-pollen palynomorphs served as the primary study methods. The results suggest relatively rapid ice retreat and establishment of ice-free ground as early as 14,560 cal BP in eastern Latvia and as early as 14,390 cal BP in central Latvia. The winter temperature was over 10 °C colder than today in Latvia and Estonia and 8 °C colder than today in Belarus during GI-1 from 14,650 to 12,850 cal BP, and latitudinal differences as an effect of the proximity of the Scandinavian ice sheet was one of the main controlling environmental factors. Winter temperatures in southern Belarus reached modern values at 10,000 cal BP, ca. 1000 years earlier than in Latvia and Estonia, where it reached modern values at 9000 cal BP. During the 8.2 ka cold event (approximately 8200 cal BP) winter temperature decreased by 2 to 3 °C, which caused environmental disturbance for ca. 700 years and vegetation alters for ca. 200 years in eastern Latvia. Likewise, phytoplankton demonstrated a strong reaction to the climate disruption, and species *Coelastrum reticulatum* and *C. polychordum* seem to be reliable for characterising the 8.2 ka cold event or increased nutrient episodes for non-pollen palynomorphs studies on lacustrine sediments in the future. The high peat decomposition and 3 °C above the modern temperature during the Holocene Thermal Maximum between 8000 and 4000 cal BP confirms the dominance of dry and warm environmental conditions, whereas cooler and wetter conditions were characteristic to the Late Holocene in Latvia. Climatic and environmental changes led to the dominance of cyanobacteria over chlorophyta and promoted thermophilous forest expansion during the Holocene Thermal Maximum. Shifts in climatic and environmental conditions occurred since 4000 cal BP in the Late Holocene. Lower amounts of birch at the local site suggest stronger regional pollen influx into the regional site. The decrease of spruce after 2000 cal BP in the wider context might support a phenomenon of large-scale decline of spruce across northern Europe. The results point toward variability in air temperature, variation in humidity and water table changes as the primary influencing factors of differences on local and regional vegetation dynamics. Although the first traces of crop cultivation in Latvia are known from the Neolithic, the palaeovegetation records indicate establishment of continuous intensive agricultural practices from AD 780 in central Latvia and from AD 1200 in northern Latvia. The results reveal a causal link between intensifying land-use and the conquest of Latvia by the Order of the Sword Brothers in AD 1200. At the same time, it is likely that the crusades and conquest of former tribal lands was not accompanied by significant impacts on rural landscapes in Livonia (present-day

territory of Latvia and Estonia), and the form and type of agriculture and land-use continued much as it had during the preceding Late Iron Age. The height of agricultural land-use in Latvia was reached between AD 1800 and 1900 when extensive farming shifted to intensive with more effective use of the existing land. Taking a long-term and multi-proxy approach offered by the palaeoenvironmental record, the current results of this thesis allow placing the new data in a broader environmental, cultural and historical context within the eastern Baltic region.

KOKKUVÕTE

Käesolevas doktoritöös analüüsitakse muutusi Baltikumi idaosa keskkonnatingimustes, taimestiku arengut ja inimmõju kogu pärastjääaegsel perioodil, so kuni ajani 14,560 kalibreeritud aastat tagasi (kal at). Selgitamaks keskkonna- ja kliimamuutuste mõju fütoplanktonile kasutati krüptomikrofossiilide (*non-pollen palynomorphs*) meetodit, mis on selles kontekstis täiesti uus lähenemine. Uuringu lähtematerjalina kasutati kolme Läti järve (Lielais Svētiņu, Āraiši, Trikātas) ja ühe soo (Mazais) setteprofiile. Läbilõigete kronoloogia põhineb konventsionaalsetel ja AMS ^{14}C dateeringutel ning sfääriliste lendtuhaosakeste loendusandmetel. Dissertatsioonis esitatud kronoloogia on kalibreeritud (kal at). Kogutud materjali analüüsil ja pärastjääaja taimestiku arengu taastuletamisel kasutati mitmeid meetodeid, peamiselt õietolmu- ja mikrofossiilide analüüsi. Saadud tulemused tõendavad, et jää taandumine 14,560 kal at Läti idaosast ning 14,390 kal at Läti keskosast toimus kiiresti. Setteläbilõigetes akumuleerunud õietolmu ja surusääskede jäänustel põhinevad kliima rekonstruktsioonid kinnitavad, et ajavahemikul 14,650–12,850 kal at (GI-1) olid Lätis ja Eestis enam kui 10 °C madalamad talvetemperatuurid, Valgevenes 8 °C madalamad, kusjuures Skandinaavia jääkilbi lähedus oli peamiseks määravaks teguriks, mis põhjustas temperatuuri põhja-lõunasuunalise erinevuse. Umbes 10,000 kal at tõusis talvetemperatuur Valgevenes sarnaseks tänapäevasega, see on 1000 aastat varem kui Lätis ja Eestis. 8200 kal at (tuntud kui 8.2 ka jahenemine) langes talvetemperatuur 2–4 °C, mille mõju keskkonnale Läti idaosas kestis ca 700 aastat ja taimestikule ca 200 aastat. Samuti mõjutas kliima jahenemine fütoplanktoni liigilist kookseisu järves ja liigid nagu *Coelastrum reticulatum* ja *C. polychordum* näivad olevat sobivad indikaatorid ka tulevikus 8.2 ka jahenemise ja/või toitainete suurenenud sissekande uuringutes. Turba suur lagunemisaste ja tänapäevasest 3 °C kõrgem aasta keskmine temperatuur Holotseeni Kliimaoptimumi ajal 8000–4000 kal at tõendab valdavalt kuiva ja sooja kliima olemasolule, mis Hilis-Holotseenis asendus jahedama ja niiskema kliimaga. Muutused kliima- ja keskkonnatingimustes Holotseeni Kliimaoptimumi ajal põhjustasid sinivetikate vohamist ja rohevetikate vähenemist ning soosisid soojalembeste puuliikide kasvu. Umbes 4000 kal at toimusid muutused kliima- ja keskkonnatingimustes. Kase õietolmu osatähtsuse vähenemine väikestes ja tõus suurtes settebasseinides viitab, et viimastesse on õietolm sissekantud kaugemalt. Kuuse õietolmu vähenemine viimase 2000 aasta jooksul toetab üle kogu põhjapoolse Euroopa täheldatud kuuse leviku laiaulatuslikku vähenemist. Tulemused näitavad, et temperatuuri, niiskuse ja veetaseme muutlikkus olid peamised põhjused, mis mõjutasid lokaalse ja regionaalse taimkatte dünaamikat. Kuigi esimesed jäljed teravilja kasvatusest Lätis on teada juba

Neoliitikumist, näitavad paleobotaanilised uuringud pidevat intensiivset põllundust alates AD 780 Läti keskosas ja alates AD 1200 Läti põhjaosas. Saadud uudsed andmed viitavad põhjuslikule seosele maaharimise intensiivistumise ja Läti hõivamise vahel Mõõgavendade Ordu poolt AD 1200. Näib, et varasem sugukondliku maa anastamine ei mõjutanud oluliselt põllumajanduslikku maakasutust Liivimaal (tänapäevasel Eesti ja Läti territooriumil) ning maaharimine jätkus sarnaselt eelneva noorema rauaajaga. Põllumajandusliku maakasutuse kõrgpunkt jäi aastate 1800–1900 vahele, kui ekstensiivne maaviljelus asendus intensiivse, enam tõhusama maakasutusega.
Arvestades paleoandmestikku ajalist ulatust ja kasutatud metoodika paljusust paigutuvad käesoleva dissertatsiooni raames saadud tulemused laiemasse keskkonna-, kultuurilisuse- ja ajaloolisse konteksti Balti regiooni idaosas.

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Lateglacial vegetation dynamics in the eastern Baltic region between 14,500 and 11,400 cal yr BP: A complete record since the Bølling (GI-1e) to the Holocene

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ABSTRACT

This paper discusses a complete record of vegetation history since the Bølling (GI-1e) warming (14,500 cal yr BP) up to the Holocene in Latvia. To date, this is the only complete record of such age in the eastern Baltic area and the northernmost area for which Bølling records are present. Combining pollen evidence, pollen accumulation rates (PAR) and plant macrofossil data, we assess the local and regional vegetation development, and we attempt to separate the true Lateglacial vegetation signal by removing the obviously redeposited thermophilous pollen; however, we remove not only their signal, we discuss the possibilities of separating the redeposition signal of the so-called "local Lateglacial trees", pine and birch, by looking at their corrosion and degradation. The results show that the Bølling warming in the eastern Baltic area was a treeless tundra community consisting of the shrubs *Betula nana*, *Dryas octopetala* and *Salix polaris*. The Older Dryas cold spell is clearly recognised as a decline in the total concentration of plant macrofossils and PARs at between 14,200 and 13,500 cal yr BP. At 13,460 cal yr BP, the *B. nana* macrofossils disappear, and tree birch (*Betula* sect. *Albae*) appears, marking the start of tree birch forest. The presence of pine forest is confirmed by a variety of macrofossils, including bark, wood, needles and seeds, since 13,400 cal yr BP, at the same time at which pine stomata are found. The first identified pine stomata finds are associated with a *Pinus* PAR over 3000 grains $cm^{-2}\,yr^{-1}$ and pine macrofossil finds with a *Pinus* PAR over 4000 grains $cm^{-2}\,yr^{-1}$. During the warmest period of the GI-1a (Allerød) at 13,000–12,700 cal yr BP, a pine forest with deciduous trees (birch – *Betula pendula* and aspen – *Populus tremula*) developed in the study area. The Younger Dryas (GS-1) cooling strongly affected the floral composition in eastern Latvia. The PAR of the tree taxa declined abruptly from a maximum value at 12,700 to below 1000 grains $cm^{-2}\,yr^{-1}$ at 12,600 cal yr BP. The response time for the pine forest to collapse was 100 years according to the PAR data. Pine macrofossils disappear simultaneously with the pollen signal at 12,600 cal yr BP, yet occasional *Pinus* stomata are recorded throughout the Younger Dryas (GS-1). The landscape was treeless shrub tundra again, with *D. octopetala, S. polaris, B. nana* and *Juniperus* present. *Picea* is introduced in the region within the cold Younger Dryas and is represented by stomata (12,400–12,200 cal yr BP), needles, seeds and wood (since 12,050 cal yr BP up to the Holocene). The Pleistocene/Holocene boundary at 11,650 cal yr BP is marked by changes both in vegetation composition and sediment type. The organic rich gyttja accumulated instead of silts and clays, and the start of the Holocene warm period permitted forest re-expansion in eastern Latvia.

1. Introduction

Understanding the long-term dynamics of ecosystems is critical to predicting their response to future environmental changes. The postglacial environmental and climatic change with abrupt cooling, which interrupted the general warming trend as new land surfaced from under the ice cap of the last glaciation, has been studied for approximately a hundred years (Hartz and Milthers, 1901; Andersson, 1909; Hausen, 1913). These studies have revealed changes and rates of changes in Earth's climatic system as well as locations of plant refugia, vegetation recolonisation routes and speeds (e.g., Bennett et al., 1991; Tarasov et al., 1999, 2000; Ravazzi, 2002; Ohlemüller et al., 2011). Palaeoecological records preserved in sedimentary deposits can provide unique insight into the nature of past ecosystems and the long-term plant population and plant community dynamics. Alongside the traditional Quaternary geological methods in investigating the glacial refugia and recolonisation, molecular tools (Taberlet et al., 1998; Sinclair et al., 1999;

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Hewitt, 2000; Petit et al., 2003; Cottrell et al., 2005) are applied to more precisely locate the plant refugia and regeneration from them. New evidence of Lateglacial (LG) habitat mammals, such as the woolly mammoth and the reindeer, moving together with the receding ice front and the open tundra strip, gives independent flora/community background to these areas (Ukkonen et al., 2006, 2011). The concept of treeless tundra in the eastern Baltic region fails to explain the rapidity of the LG and postglacial tree population dynamics of the region, showing that tree populations were present there at times (Heikkilä et al., 2009) and vanishing at others. Abrupt LG reversing climate change events occurred over the span of decades, such as in the Younger Dryas 12,850–11,650 cal yr BP (Lowe et al., 2008), when the cooling average summer temperatures dropped by approximately 3–4 °C, followed by a 7 °C warming in just 20–50 yr based on Greenland data (Dansgaard et al., 1989; Alley et al., 1993). Such reversals influenced the postglacial succession of flora and fauna (e.g., Litt and Stebich, 1999; Birks and Ammann, 2000; Lotter et al., 2000; Lõugas et al., 2002; Birks and Birks, 2004; Mortensen et al., 2011).

LG studies in the eastern Baltic area span over a century, focussing on ice-recession lines and chronology (Kalm, 2006). In recent years, new data on ice retreat were obtained with the help of varvochronology (Sandgren et al., 1997; Hang, 2003), new dating methods (Rinterknecht et al., 2006; 2008), palaeobotanical data (Saarse et al., 2009; Amon and Saarse, 2010; Amon et al., 2010, 2012; Kihno et al., 2011) and discussed in review papers (Raukas et al., 2004; Kalm et al., 2011).

This paper discusses a complete record of vegetation history since the Bølling warming (14,500 cal yr BP) up to the Holocene and is thus far the only record of this age in the eastern Baltic area and the northernmost area where Bølling records are available. We combine pollen evidence, pollen accumulation rate (PAR) and plant macrofossil data to assess the local and regional vegetation development. We attempt to separate the contemporary LG vegetation signal from the noise (caused by the reworked pollen from the older sediments) by removing (a) obviously redeposited thermophilous pollen and (b) corroded and degraded pollen of the so-called "local LG trees", such as pine and birch, which will perhaps help us to understand more precisely the LG vegetation in the eastern Baltic and elsewhere.

Fig. 1. Schematic relief map of the Baltic region showing the Lateglacial sites discussed in the text with the location of the Scandinavian Ice Sheet ice marginal zones as red lines (compiled from Kalm, 2006; Kalm et al., 2011). Ages of the ice marginal zones are from Saarnisto and Saarinen (2001), Saarse et al. (in press-a,in press-b), Amon and Saarse (2010), Kihno et al. (2011) and Kalm et al. (2011).

2. Study area

Lake Lielais Svētiņu (LS) is located in eastern Latvia, Rezekne district (56°45.5 N; 27°08.8 E), in the Lubana depression between the Latgale and Vidzeme uplands (Fig. 1). The area of the lake is 18.8 ha, the altitude is 96.2 m above sea level (a.s.l.), the mean depth is 2.9 m and the maximum depth is 4.9 m. The oblong brown-water humic water body belongs to the Daugava watershed area and has small inlets and outlets. The topography around the lake undulates, reaching up to approximately 100 m a.s.l., and the slope angle to lake shore is low. The highest estimated LG shoreline in the area is 108 m a.s.l. The Quaternary cover consists mainly of silts and clays of the Lubana basin, which have been greatly paludified in the Holocene. Forested areas (birch forest) and a few farms surround the lake today.

3. Material and methods

3.1. Coring and lithostratigraphy

The sediment was cored from lake ice using a 10-cm-diameter Russian corer in March 2009. The water depth below ice was 4 m. The sediment thickness reached 11.35 m of which the LG portion was the lowermost 3.75 m. In the present article, we used sample depths from the ice/water surface. Multiple parallel overlapping sediment cores were described in the field, photographed, carefully packed into 1 m plastic semi-tubes, wrapped in polyethylene film, labelled and transported to the laboratory for further analyses. The LG interval of the sediment core was analysed for the present study. The Holocene sediment was transported to Latvian University for additional analyses. The organic matter (OM) content of the sediment was determined by loss-on-ignition at 550 °C for 4 h (Heiri et al., 2001). The magnetic susceptibility (MS) was measured with a Bartington MS2E meter (Nowaczyk, 2001).

3.2. Chronology

Several samples containing material suitable for radiocarbon dating were selected and packed separately directly in the field, while most of the dating material was identified after sediment sieving in laboratory. Only terrestrial plant macrofossils were chosen as suitable material for radiocarbon dating, including twigs, bark, wood and seeds. The identified and cleaned specimens were sent to the Poznan Radiocarbon Laboratory, Poland. In total, 12 horizons were dated. The dates were calibrated, and an age–depth model was built with an OxCal 4.1 depositional model, including visible sedimentary boundaries (Reimer et al., 2004; Bronk Ramsey, 2008).

3.3. Palaeobotanical methods

The preparation for plant macrofossil analysis followed conventional procedures (Birks, 2001). The cores were sliced into 5-cm-thick intervals, and all material remaining after other analyses was used for plant macrofossil analysis. The sub-samples were determined by water displacement in a measuring cylinder. The sample size varied from 90 to 730 cm^3. The samples were wet-sieved through a 0.16 mm mesh. Material retained on the sieves was examined using a stereo and light microscope. The plant macrofossils were identified according to the relevant literature (Berggren, 1969; Anderberg, 1994; Cappers et al., 2006) and a reference collection. The counts were recalculated to a concentration (plant macrofossils per 1 cm^3). Seeds of tree-type birch (*Betula pendula* and *Betula pubescens*) were grouped as *Betula* sect. *Albae*, and *Carex* seeds were divided into two groups by seed morphology: triangular seeds and lenticular seeds.

The pollen sample preparation followed a standard acetolysis method (Berglund and Ralska-Jasiewiczowa, 1986) combined with a cold concentrated 40% HF treatment followed by a hot concentrated 70% HF treatment to remove inorganic matter (Bennett and Willis, 2001). *Lycopodium* spores were added to calculate pollen concentration and, subsequently, the PAR values (Stockmarr, 1971). A pollen sum of at least 500 grains was obtained. The pollen data were expressed as percentages of the total terrestrial pollen sum, and the PAR values were expressed as pollen grains $cm^{-2}\,yr^{-1}$. Counts of spores, green algae, charcoal, and other microfossils were calculated as percentages of the total sum of terrestrial pollen. The *Betula nana*-type was differentiated from *Betula* on the basis of size and morphology (Mäkela, 1996; Caseldine, 2001). Corroded and degraded grains of *Betula* were counted separately during routine pollen analysis and used as a measure of redeposition or inwash from older sediments (Birks, 1970). These grains were compared with the ratio of *Betula* versus *Betula nana*-type pollen. Intact (unbroken) *Pinus* pollen grains were counted separately from the 'one air-sacked' or broken grains (two air-sacks count as one *Pinus* pollen grain), and the relationship of pine versus broken pine pollen was used as a measure of pine redeposition.

For diatom analysis, freeze-dried, weighted sediment sub-samples were digested in 30% H_2O_2 until the organic material was oxidised. A few drops of 10% HCl were added to remove carbonates, and thereafter, the fine mineral particles were removed by repeated decantation. Divinylbenzene microscopic markers were added to determine diatom concentration. A few drops of the cleaned sub-sample were dried onto the cover glass and mounted onto slides using a Naphrax medium and were analysed for microfossils under an Axio Imager light microscope at $\times 1000$ magnification using oil immersion and differential interference contrast optics. The diatoms were identified using standard floras, and they were grouped according to their habitat into planktonic and periphytic taxa, the latter including epipelic, epipsammic and epiphytic life forms.

Pollen diagrams and macrofossil data were compiled using Tilia 1.0.1 (Grimm, 2007). The zonation of pollen and plant macrofossils was based on the binary splitting of the sum-of-squares method using the PSIMPOLL 4.10 programme (Bennett, 2002). The significance of statistically determined zones was estimated by comparison with the broken-stick model described by Bennett (1996). Macrofossil zonation using PSIMPOLL is based on macrofossil data for vascular terrestrial plants.

4. Results and interpretation

4.1. Lithostratigraphy and chronology

The LG to early Holocene sediments from Lake LS were divided into 8 lithostratigraphical units (Table 1). The LG sediments consisted of sand, silt and laminated or varved clay. Several intervals contained dark, probably dispersed OM. The maximum OM content in the LG sediments was 7.9% at a depth of 1227 cm. Increasingly OM-rich gyttja started to accumulate in the early Holocene. The MS data have three periods of increased values: in the basal layers, in the mid-Allerød and in the Younger Dryas (Fig. 2, Table 1).

The chronology is based on 11 radiocarbon age estimations of terrestrial plant macrofossils (Table 2). By extrapolating the acquired age determinations to the basal part of the sediment record, we estimated the start of sedimentation in Lake LS at 14,560 cal yr BP. The model shows a poor agreement index ($A = 40$) at the 1445 cm level, and the dating was rejected on the basis of that value.

4.2. Fossil pollen record

4.2.1. Fossil pollen assemblages

The LG pollen record of Lake LS comprised 48 sample levels and 88 microfossil types, which were divided into 7 statistically significant local pollen assemblage zones LPAZ (Fig. 3, Table 3). These zones roughly corresponded to the boundaries of the lithostratigraphical units and are interrelated with the plant macrofossil data. The sediment accumulation rate (AR) was relatively constant, ranging between 0.16 and 0.8 $cm^{-2}\,yr^{-1}$; thus, the pollen sample resolution was, on average, 65 years.

4.2.2. Corroded and redeposited pollen

Tree pollen that was considered exotic to the LG environment, such as thermophilous taxa *Alnus*, *Corylus*, *Tilia*, *Quercus*, *Ulmus*, *Fraxinus*, and *Carpinus*, presumably inwashed from older deposits, was summarised as "redeposited pollen" (Fig. 3). Several of above mentioned pollen, but also some of the *Betula* pollen grains, which are usually considered to be locally produced, seemed corroded and degraded. Grains of more smooth-surfaced pollen types, such as *Betula*, *Alnus*, *Corylus* and *Carpinus*, but also *Tilia* and *Ulmus*, were ascribed corrosion estimates (corroded/not corroded) and later used as a measure of redeposition or inwash from older sediments.

Table 1
Lithostratigraphy of Lake Lielais Svētiņu Lateglacial and early Holocene sediments.

Depth from water surface, cm	Age, cal yr BP	Sediment description	Organic matter content, %	MS values, 10^{-5} SI units
1105–1160	11,650–10,910	Silty gyttja, greenish brown, homogeneous	4.2–13.6%	1.5–11.8
1160–1190	12,060–11,650	Silt, dark grey, with organic matter	3.7–6.9%	9.6–29.6
1190–1268	12,730–12,060	Silt, light grey	3.0–7.9%	8.6–30.7
1268–1317	13,310–12,730	Silt, yellowish, with organic matter	3.3–6.3%	10.0–25.9
1317–1332	13,400–13,310	Clay, distinctly laminated (varved clay?), about 20 lamina couplets	1.8–3.7%	13.0–24.8
1332–1498	14,250–13,400	Silt, grey, increasingly dark coloured from organic matter towards the upper limit	1.5–5.3%	8.3–23.5
1498–1515	14,390–14,250	Sand, dark coloured, with organic matter	1.9–3.2%	15.4–39.4
1515–1535	14,560–14,390	Sand, beige, compact	1.9–2.5%	6.0–29.5

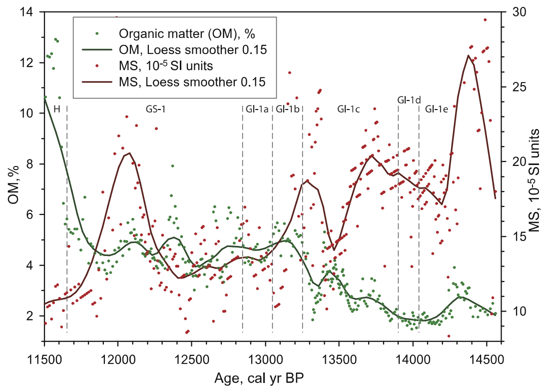

Fig. 2. Organic matter (OM) content and magnetic susceptibility (MS) variability for Lake Lielais Svētiņu sediments plotted against Greenland NGRIP event stratigraphy.

While the percentage of corroded *Ulmus*, *Tilia* and *Carpinus* pollen grains was always 100%, that of *Alnus* and *Corylus* varied between 75 and 100%. The percentage of redeposited pollen shows a reversed distribution in comparison with OM values, relative abundance of tree pollen types and tree pollen PAR (Fig. 4). The percentage of corroded/destroyed birch pollen grains versus non-corroded/non-destroyed pollen is clearly smaller in LPAZs LSP-2, LSP-5 and LSP-7. The goodness-of-fit (R^2) between the sum of redeposited pollen and the corroded *Betula* was 0.55. If an average value over three samples is used, the R^2 increases to 0.71 (Fig. 5), indicating a good correlation. The relationship between *Betula* tree-type pollen and *Betula nana*-type pollen (indicated as the deviation from the mean value) shows a good positive correlation with dwarf birch macrofossil finds (Fig. 6A), i.e., in periods in which dwarf birch macrofossils are present, the deviation is in favour of *Betula nana*-type pollen, and corroded birch pollen dominates. Deviation from the mean ratio of *Pinus* versus "one air-sacked *Pinus*" (P/osP) shows a highly negative deviation, i.e., more broken pine pollen in periods in which the pine PAR is low and there are no pine macrofossils (Fig. 6B). Interestingly, the ratio of P/osP in the LG deposits of Lake Udriku, North Estonia (Amon and Saarse, 2010), is always very low (unpublished data), which is indicated as an additional broken line in Fig. 6A. In general, the Holocene ratio of P/osP measured in several Estonian pollen datasets is comparable with the values of LS pine pollen in the period of 13,700–12,750 cal yr BP (Fig. 6), where we assume pine forest was present according to a high pine PAR and macrofossil evidence. The assumption that part of the birch and pine pollen is also redeposited in LG sediments, likewise the thermophilous pollen grains, is obvious. The question is how much of that pollen is redeposited. We think that by using the degradation data of pine and birch pollen in combination with plant macrofossil evidence, we could subtract a certain portion of pollen grains from the record and give a more accurate picture for the LG vegetation.

4.3. *Plant macrofossil evidence of vegetation change*

The Lake LS LG sediment record was divided into 77 samples for plant macrofossil analysis, and in total, more than 31.5 L of sediment was examined for plant remains. A total of 30 vascular plant species, genus or families were identified. The concentration of plant macrofossils was multiplied by 100 to plot the results on a diagram (Table 4, Fig. 7), therefore presenting the number of macrofossils in 100 cm^3.

4.4. *Diatoms and other aquatic organisms*

Most of the sediment sequence was devoid of diatoms; however, an abundant diatom assemblage was ascertained between the period of 13,300 and 13,000 cal yr BP. Altogether, 76 diatom taxa belonging to 27 genera were encountered. The taxa that occur at a high relative frequency include epipsammic, small-sized fragilarioid diatoms, such as *Fragilaria brevistriata*, *F. construens*, *F. construens* var. *venter* and *F. lapponica*, as well as epipelic *Amphora pediculus*, *Campylodiscus noricus* and *Gyrosigma attenuatum*. Planktonic diatoms are relatively rare (1–3%). Although the diatom composition does not show considerable changes, the diatom concentration has sudden and short-lived peaks at 13,200 and 13,000 cal yr BP, which is synchronous with the curve of green algae AR (Fig. 8). The ARs of green algae (*Pediastrum*, *Tetraedron*, *Scenedesmus* and *Botryococcus*) as well as Cladocera are high at intervals spanning 14,400–14,200 and 13,300–12,700 cal yr BP and in the Holocene.

5. Discussion

5.1. *Deglaciation of eastern Baltic area and associated pioneer vegetation communities*

Lake LS is situated in the East Latvian glacial lowland (Zelčs and Markots, 2004) between the Vidzeme and Latgale glacial uplands. The area was shaped and influenced by the Lubana glacier system, which was part of a larger ice stream complex that extended to Western European Russia and Lake Ladoga, and it entered the Lubana basin from the northeast (F1 ice stream in Kalm, 2010). The dynamics of ice lobes were largely controlled by bedrock and topography prior to the Last Glacial Maximum (Zelčs and Markots, 2004), climate and connection with source areas. Geomorphologically, Lake LS and the East Latvian lowland are situated between the Middle and North

Table 2
Radiocarbon ages of Lake Lielais Svētiņu sediment core. The weighted average ages of the deposition model in OxCal 4.1. (Bronk Ramsey, 2001; Reimer et al., 2004) in column 5 were used in the age–depth model.

Depth, cm	Laboratory code	^{14}C date, yr BP	Calibrated age, cal yr BP, 2σ	Model age, cal yr BP	Material dated
1157	Poz–30426	10,100 ± 60	11,650–11,590	11,620 ± 20	Wood
1185	Poz–36710	10,270 ± 50	12,140–11,810	11,990 ± 90	Twigs
1215	Poz–31768	10,330 ± 50	12,400–12,120	12,290 ± 80	Wood
1261	Poz–31769	10,760 ± 50	12,760–12,560	12,660 ± 50	Twigs, bark
1315	Poz–36711	11,460 ± 60	13,400–13,160	13,290 ± 60	Bark
1355	Poz–36712	11,670 ± 60	13,620–13,400	13,510 ± 50	Stems
1365	Poz–36715	11,630 ± 60	13,660–13,460	13,560 ± 50	Twigs, *Betula nana* leaves, *Potentilla* seed
1400	Poz–36713	11,840 ± 60	13,830–13,640	13,740 ± 50	Twigs
1445	Poz–36714	12,410 ± 60	14,240–13,990	14,110 ± 60	Twigs, *Betula nana* leaf (rejected from model)
1492	Poz–31770	12,380 ± 60	14,440–14,040	14,220 ± 100	Twigs, bark
1510	Poz-29298	12,420 ± 60	14,590–14,150	14,350 ± 110	Wooden material
1530	Poz–31771	12,350 ± 60	14,950–14,180	14,520 ± 210	Wooden material

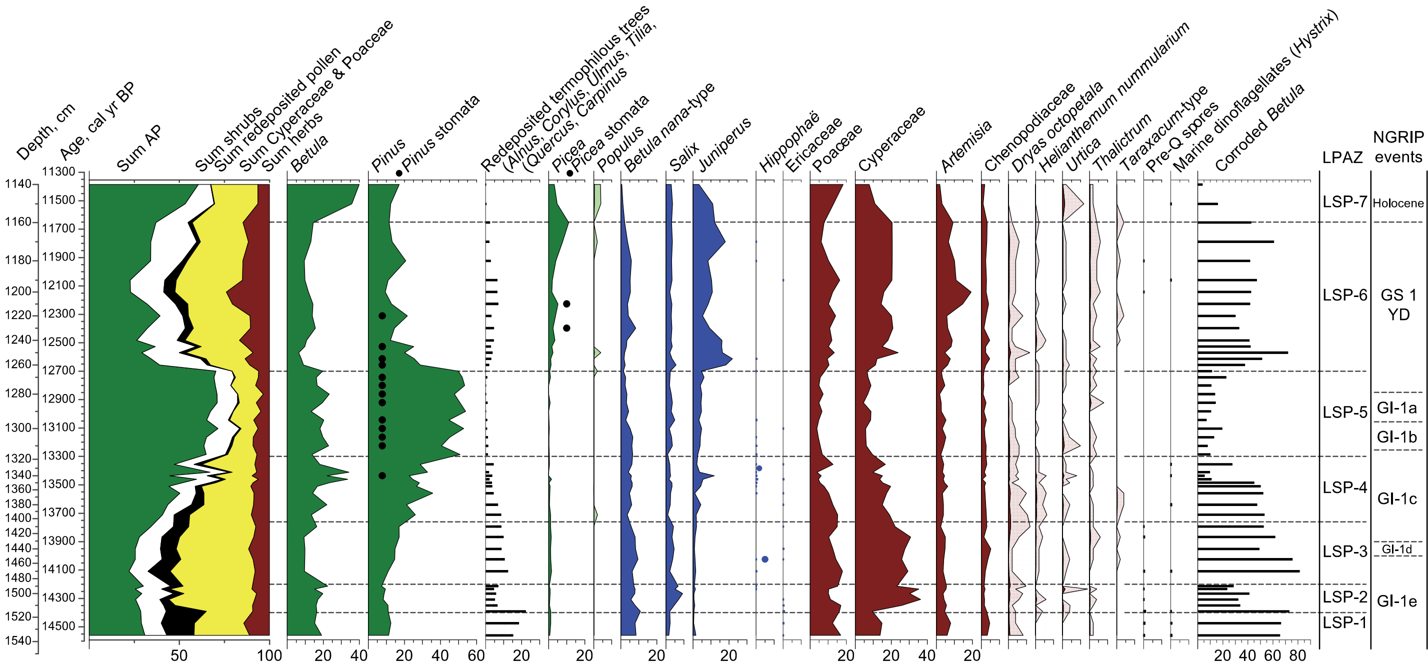

Fig. 3. Lake Lielais Svētiņu sediment profile percentages of selected pollen types and other microfossils (shading in pink for the herbs from *Dryas* to *Taraxacum*-type is an exaggeration at ×10); statistically significant local pollen assemblage zones (LPAZ) compared with Greenland NGRIP events are shown.

Table 3
Lake Lielais Svētiņu statistically significant local pollen assemblage zones (LPAZ)

Depth, cm	Age, cal yr BP	LPAZ	LPAZ description	Vegetation type
1140–1160	11,650–11,390	LSP-7	AP dominates up to 60%, *Betula* reaches 40%, *Ulmus* and *Populus* appear, shrubs and NAP decline slightly. Corrosion is low. PAR of AP rises to Holocene levels.	Holocene, forest expansion
1160–1265	12,700–11,650	LSP-6	AP/NAP ratio is roughly 30/70, tree types *Betula* and *Pinus* are less than 20%, *Picea* is present as pollen and occasional stomata, of shrubs *Juniperus* culminates (20%). The NAP is dominated by Cyperaceae, Poaceae, *Artemisia*, Chenopodiaceae, *Dryas octopetala*, *Thalictrum* and *Helianthemum nummularium*. High relative abundance of corroded and inwashed pollen grains is observed. *Betula* and *Pinus* PARs are generally under 1000 grains cm^{-2} yr^{-1}.	Younger Dryas, open forest tundra with scattered birch, pine and spruce
1265–1315	13,300–12,700	LSP-5	AP dominates up to 70%, *Pinus* reaches over 50%, pine stomata are recorded, shrubs, NAP and redeposited pollen grains decrease. Green algae flourish. *Betula* PAR stays around 4000 and *Pinus* PAR increase to an astonishing 14,000 grains cm^{-2} yr^{-1}.	Allerød warming, mixed pine-birch forest with a distinct dominance of pine
1315–1405	13,760–13,300	LSP-4	AP share gradually rises at the expense of NAP and around 13,600 cal yr BP surpasses it. *Pinus* and *Betula* PARs reach over 1000 grains cm^{-2} yr^{-1} 13,650 cal yr BP, *Betula* PAR peaks at 13,300 cal yr BP and stays around 4000 grains cm^{-2} yr^{-1}. All water plants and animals thrive since 13,400 cal yr BP.	Early-Allerød, developing birch-pine forest tundra
1405–1490	14,200–13,760	LSP-3	NAP dominates over AP (20%). The sum of redeposited thermophilous trees is high. *Betula*/*Betula nana*-type relationship is in favour of the latter. *Hippophaë* appears. *Pinus* and *Betula* PARs stay under 500 grains cm^{-2} yr^{-1}.	The GI-1d (Older Dryas) cooling, treeless pioneer tundra
1490–1515	14,400–14,200	LSP-2	AP/NAP ratio is 40/60; tree types *Betula* and *Pinus* are less than 20%, shrubs *Betula nana* and *Salix* are present. The NAP part is dominated by Cyperaceae, Poaceae and *Dryas octopetala*. Low relative abundances of corroded and inwashed thermophilous pollen grains. *Betula* PAR is just over 500 grains cm^{-2} yr^{-1}, *Salix* PAR reaches 300 grains cm^{-2} yr^{-1}. AR of green algae *Pediastrum* and *Tetraedron* are high.	The GI-1e (Bølling) warming, treeless herb/shrub tundra. Higher productivity in lake
1515–1535	14,560–14,400	LSP-1	NAP dominates over AP. The sum of redeposited thermophilous trees is highest, over 20%. *Bryales* mosses which are present throughout the LG are missing in this zone. *Betula nana*-type peaks. Tree pollen PARs are below 500 grains cm^{-2} yr^{-1}.	Early-Bølling, treeless pioneer tundra, establishment of vegetation cover

Lithuanian (Haanja) Moraine (Rinterknecht et al., 2006) and consequently, based on ^{14}C and ^{10}Be dates from these ice marginal formations, they date approximately to 13,500 ± 1000 ^{14}C yr BP (~13,500 ^{10}Be yr BP) and 13,300 ± 1100 ^{14}C yr BP (~13,300 ^{10}Be yr BP), respectively (Rinterknecht et al., 2008). In calibrated years (OxCal 4.1, Intcal09), the median ages of the above mentioned ^{14}C ages and thus also the glacier retreat from the East Latvian lowland would be approximately 16,300–16,000 cal yr BP. Zelčs and Markots (2004) estimate the age of the North Lithuanian Moraine (Linkuva, Haanja) as approximately 13,200 ^{14}C yr BP (calibrated median ca 16,000 cal yr BP). Kalm (2006) proposed the age of the Haanja Moraine to be 15,700–14,700 cal yr BP, later pinpointing it to approximately 15,000 cal yr BP (Kalm et al., 2011). Thus far, the age estimations tend to be too old compared with those of Kalm et al. (2011), possibly because of the controversial ages of the Raunis section (Fig. 1) in northern Latvia. The ^{10}Be ages seem to be rather young; the possible problem with ^{10}Be ages is that we do not know when the rock surfaces of the glacial erratic boulders that were dated melted out of the glacier, whether it was soon after the glacier retreated or when the erratic boulders were hidden in dead ice fields for ages.

The interpreted deglaciation processes based on age estimations of ice marginal formations suggest a rather slow ice retreatment rate. A large Lubana ice-dammed lake with a maximum water level

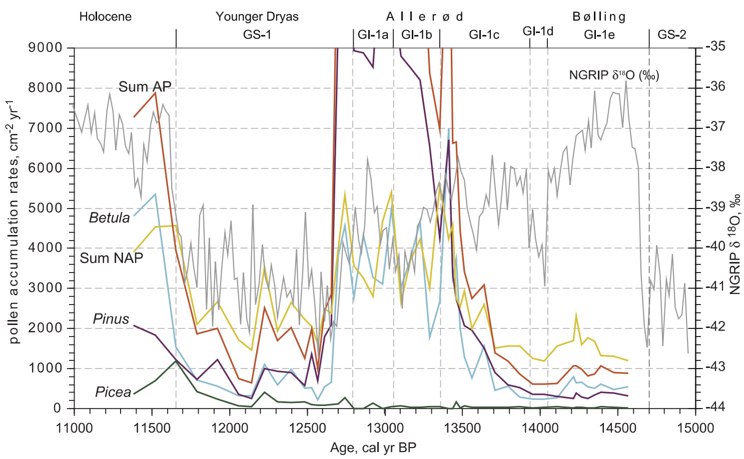

Fig. 4. Pollen accumulation rates of selected tree pollen types and the NAP total of the Lake Lielais Svētiņu sediment profile plotted against NGRIP $\delta^{18}O$ (‰) data (Rasmussen et al., 2006).

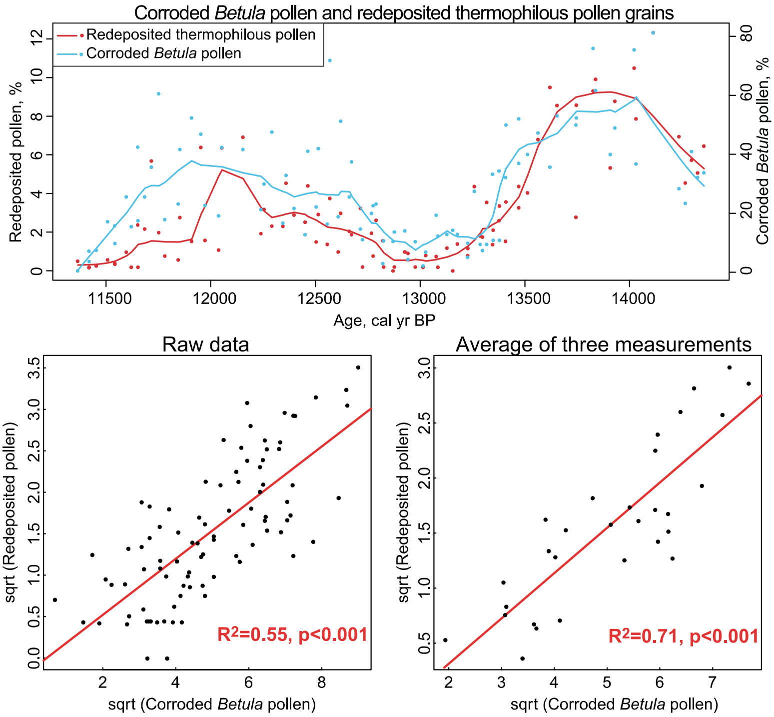

Fig. 5. Corroded and degraded grains of *Betula* and redeposited thermophilous pollen grains (*Alnus*, *Corylus*, *Carpinus*, *Quercus*, *Ulmus*, *Tilia* pollen types). The goodness-of-fit (R^2) between the abundance data for redeposited thermophilous, i.e., inwashed pollen, and the corroded *Betula* pollen is 0.55 (R^2 for the three measurement average is 0.71).

altitude of 108 m a.s.l. (Zelčs and Markots, 2004) flooded the area afterwards, and Lake LS might have been in its southeastern part. The establishment of virgin terrestrial ice-free ground and the development of vegetation in the surroundings of Lake LS in eastern Latvia occurred at 14,560 cal yr BP, as derived from the age model (zones LSP-1 and LSM-1; Figs. 3 and 7), in the relatively warm climatic oscillation of the LG, which is termed GI-1e (*sensu* Lowe et al., 2008). By that time, the environmental conditions were suitable to support pioneer vegetation. Pollen and plant macrofossil analysis results suggest that the pioneer communities around Lubana basin in the glacial foreland were rather scarce: only two seeds of *Carex* were found, and the pollen spectra contain numerous pollen grains of redeposited thermophilous trees (*Alnus*, *Corylus*, *Carpinus*, *Quercus*, *Ulmus* and *Tilia*) in total 20%, of which over 70% were also corroded. Marine dinoflagellates (*Hystrix*) and pre-Quaternary spores are common, suggesting the reworking of older material. A similar reworking of pollen in the early LG sediments had already been noted by Iversen (1954) at the classic Bølling Sø site in Denmark. The pine and birch pollen PARs are below 500 grains cm^{-2} yr^{-1} (Fig. 4), and the proportion of corroded birch pollen is above 70% (Fig. 3), suggesting, rather, that they were not present in the vegetation. The *Betula nana*-type pollen percentages are the highest in this pioneer phase, and the deviation from the mean ratio of dwarf birch versus birch pollen (Fig. 6A) indicates positive anomalies, although *B. nana* macrofossils appear only at 14,400 cal yr BP, i.e., approximately 100 years after the deglaciation. Highly negative anomalies occur in the deviation from the mean pine degradation, pointing also to high pollen resedimentation and not to the local production of any tree pollen. If we subtract the supposedly redeposited portion of pine and birch pollen according to the level of degradation of pine pollen (P/osP = 75%) and the corrosion of birch pollen (mean = 68.3%) from the total record, we end at PARs below 100 grains cm^{-2} yr^{-1} for pine and 200 grains cm^{-2} yr^{-1} for birch, which are far below the limit of presence for these taxa in present conditions (Hicks, 2001).

However, the favourable climatic conditions during phase GI-1e (in older scientific literature, the described first postglacial stable community is often named “Bølling”) allowed the pioneer community to be replaced by a stable and more species-rich vegetation type in ca 100 years (LSP-2 and LSM-2). Most likely, a treeless tundra community consisting of shrubs (*B. nana*, *Dryas octopetala*, *Salix polaris*) and telmatic plants (*Carex*, *Juncus*) spread between 14,400 and 14,200 cal yr BP, as there is no macrofossil evidence of tree birch. The *Betula* sp. undiff. seed curve (Fig. 7) in this time interval should be regarded as *B. nana*; although later, in Allerød, the same curve most likely indicates tree birch. To date, tree birch evidence from the Bølling period is also lacking in Denmark (Mortensen et al., 2011). The amount of plant macrofossils from this sediment interval is surprisingly high, hinting at a rather productive community supported by suitable climatic and environmental conditions. Another reason might be the extreme openness of the landscape that favoured fast transportation of plant remains into the lake and, therefore, good preservation in the sediment record. A third assumption regarding the richness of plant macrofossils may point to the origin of Lake LS; namely, the OM-rich Bølling strata may be formed *in situ* on top of the degrading ice field when material melting out of the glacier ice forms a wet soil cover on top of the ice. This scenario is contradicted, however,

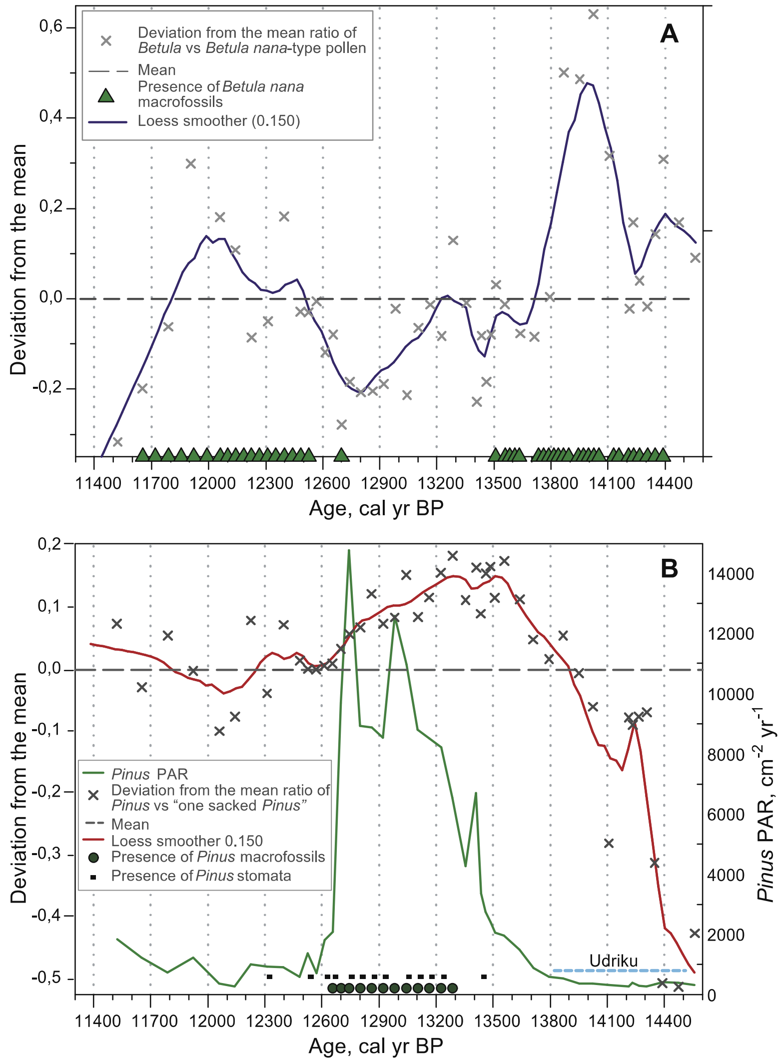

Fig. 6. A. The relationship between *Betula* tree-type pollen and *Betula nana*-type pollen, indicated as deviation from the mean value in relation to dwarf birch macrofossil finds. When dwarf birch macrofossils are present, the deviation is in favour of *Betula nana*-type pollen, and corroded birch pollen dominates, as in Fig. 5. B. Deviation from the mean ratio of *Pinus* versus "one air-sacked *Pinus*" (P/osP); more broken pine pollen is present in periods in which the pine pollen accumulation rate (PAR) is low and there are no pine macrofossils. The ratio of P/osP in the Lateglacial (LG) deposits of Lake Udriku, North Estonia (Amon and Saarse, 2010), where tundra conditions prevailed over the whole LG period and tree pollen was absent at all times, is constantly very low (unpublished data), indicated as a broken line in the bottom right.

by a number of aquatic species, both green algae and cladocera, which indicate lacustrine conditions.

Although the macrofossil data does not support presence of trees during GI-1e, the pollen evidence points to several arguments that might explain the opposite. First, the uncorrected PAR of birch reaches over 500 and up to 800 grains cm^{-2} yr^{-1} by the end of the warm period at 14,200 cal yr BP; second, the corrosion index of *Betula* drops drastically between 14,400 and 14,200 cal yr BP, which might indicate that at least some portion of the tree birch pollen rain was locally produced, or at least we cannot rule out the idea. Applying the degradation/corrosion values for this period, the PARs for pine and birch are below 200 and 500 grains cm^{-2} yr^{-1}, respectively; for the latter, this is a value close to the presence limit, but not enough to detect macrofossils. Paus (1995) argues that birch PAR values as low as 200 grains cm^{-2} yr^{-1} indicate the local presence of tree birch during the Bølling in south Norway, yet without macrofossil evidence. Currently, we remain doubtful about the presence of tree birch in Bølling in the eastern Baltic area. Approximately 14,200–14,000 cal yr BP pollen grains and other microfossils (hair of *Hippophaë*) show some climate amelioration, as occurrences of *Hippophaë* seem to precede the truly warmer periods of the LG and the Holocene. *Hippophaë* was also an important indicator of open landscape for Iversen (1947). Otherwise, the pollen and macrofossil data agree on shrub–herb tundra

Table 4
Lake Lielais Svētiņu plant macrofossil assemblage zones

Depth, cm		Age, cal yr BP	Zone	Zone description	Vegetation type
1140–1160		11,650–11,390	LSM-7	Zone is based on two samples that contain remains of conifer (*Picea*) and deciduous trees (tree birch, aspen), no shrub macrofossils were recorded. Grasses (*Typha*) and *Juncus* are present.	Mixed forest expansion
1160–1265		12,700–11,650	LSM-6	Pine and deciduous tree (tree birch, aspen) macrofossil abundance drops quickly and vanishes in the start of the zone. In the lower part of the zone, the amount of plant macrofossils is low. In upper part of zone, spruce (*Picea*) macrofossils appear, dwarf birch and *Dryas* remains re-appear in the same layers. Telmatic plants (*Juncus, Carex*), aquatic plants (*Potamogeton, Hippuris, Batrachium*) and grasses are present.	Treeless open landscape to mixed forest tundra
1265–1315		13,300–12,700	LSM-5	The assemblage changes quickly from birch forest to mixed conifer forest, dominant tree species are pine (*Pinus*) and tree birch (*Betula*). *Populus tremula* is present. The number and species composition of aquatic species is stable (*Potamogeton, Zannichellia, Hippuris*). Telmatic plants, herbs and grasses are present (*Juncus, Carex*, grasses, *Saxifraga* etc.)	Mixed conifer forest
1315–1405	1315–1350	13,500–13,300	LSM-4	*Betula nana* disappears abruptly in favour of tree birch (*Betula* sect *Albae*). Telmatic plant remains are found in every sample. Herbs (*Saxifraga*, *Alchemilla*, Poaceae) and grasses are present. *Potamogeton* spp., *Hippuris vulgaris* and *Zannichellia* remains are found in small amount indicating ameliorated conditions also in aquatic environment.	Birch forest
	1350–1405	13,760–13,500		The majority of macrofossils of this subzone are *Betula nana* leaves; *Dryas* is present in one sample. Few grasses and telmatic plant remains are found.	Tundra
1405–1490		14,200–13,760	LSM-3	The number of plant macrofossil declines. The amount of shrub and *Carex* remains decreases. *Dryas octopetala* and *Betula nana* remains are present in most samples although in small numbers. Telmatic plants (*Selaginella, Carex, Juncus*) are present. The first appearance of Poaceae and *Saxifraga* plant macrofossils. *Potamogeton* spp. endocarps are continuously present.	Shrub herbaceous tundra
1490–1515		14,400–14,200	LSM-2	Zone is characterised by remarkable rise in amount of plant macrofossils. Characteristic is abundance of *Betula nana* remains (leaves, seeds). Other shrubs present are *Salix polaris* and small quantity of *Dryas octopetala*. Wooden material is frequently found in samples. Telmatic plants are numerous (*Carex, Juncus*), *Potamogeton* spp. endocarps are present in highest concentration that refers to favourable growth conditions in lake.	Shrub wetland tundra
1515–1530		14,500–14,400	LSM-1	The samples contain no or very few plant remains (*Carex* seeds).	Pioneer community

conditions, as pollen evidence also points to an elevated signal of *Salix*, Ericaceae and herbs. An early dominance of *S. polaris* and *Dryas* has also been noted at other sites in the Nordic countries (Paus, 1995; Bennike et al., 2004b; Karlsen, 2009).

The aquatic life quickly responded to climatic amelioration (Fig. 8). The ARs of green algae *Pediastrum* and *Tetraedron* and Cladocera are high, and the total AR reached 7000 coenobia $cm^{-2}\,yr^{-1}$.

A comparable site, Lake Kurjanovas (Heikkilä et al., 2009), situated in the Mudava lowland area adjacent to Latgale upland from the east (Fig. 1), suggests that the deglaciation there was more than 16,000 cal yr BP, which is in accordance with the estimated ages of the nearby ice marginal zone (Rinterknecht et al., 2006). The Latgale upland (highest point 289 m a.s.l.) was a spreading area for two glacial complexes, F1 and F2 (Kalm, 2010). The area around Lake Kurjanovas within a different ice stream might have deglaciated earlier than the surroundings of Lake LS. Lake Kurjanovas is situated somewhat higher than Lake LS (111 m a.s.l. and 96 m a.s.l., respectively), which probably promoted earlier deglaciation and terrestrialisation. However, the time-scale of Lake Kurjanovas is rather tentatively extrapolated, and authors suggest handling the chronology for the lower part of the sediment with caution. It is likely that the start of vegetation development and its preservation in the lake sediments east of the Latgale upland took place earlier than in the eastern Latvian glacial lowland northwest of the Latgale upland.

Comparing the vegetation development, a treeless wetland shrub tundra (*B. nana*) community prevailed in the Lubana glacial lowland, while *Dryas* tundra with possible scarce tree birches existed east of the Latgale upland, around Lake Kurjanovas (Heikkilä et al., 2009).

5.2. The GI-1d cooling and vegetation recovery thereafter (14,200–13,300 cal yr BP)

The GI-1d, or “Older Dryas” in early Baltic literature, was a short cooling episode. This period, centred at 13,950 cal yr BP, is ca 125 years in the Greenland ice data (Lowe et al., 2008), before the GI-1c warmer climatic episode. The cold climate interval is also well reflected in the palaeobotanical record of Lake LS.

The total concentration of plant macrofossils declines sharply at 14,200 cal yr BP. The species composition found at 14,200–13,300 cal yr BP (plant macrofossil zones LSM-3 and the LSM-4a subzone) does not change much compared with the GI-1e warm period and still indicates a sparse treeless *B. nana*–*Dryas* tundra community, but in much lower concentrations and without woody material. The soil was dryer than in the previous time interval, and the number of telmatic remains is modest. Instead, grasses and *Saxifraga aizoides* appeared. The latter species prefers stony and barren alkaline soils as a growing environment. Since

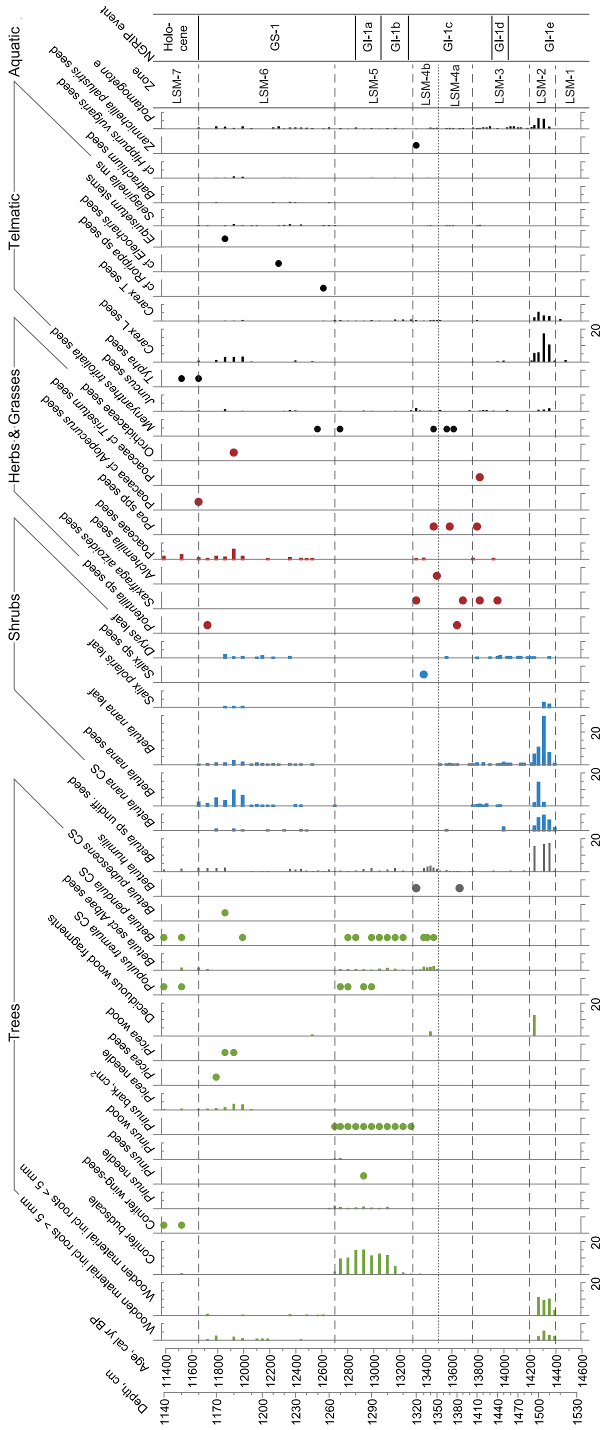

Fig. 7. The concentration of plant macrofossil and limnic animal remains per 100 cm^3 of sediment and macrofossil assemblage zones from the Lake Lielais Svētiņu sediment profile. Dots mark low concentration of given species. Abbreviations: CS – catkin scale; MS – megaspore; e – endocarp.

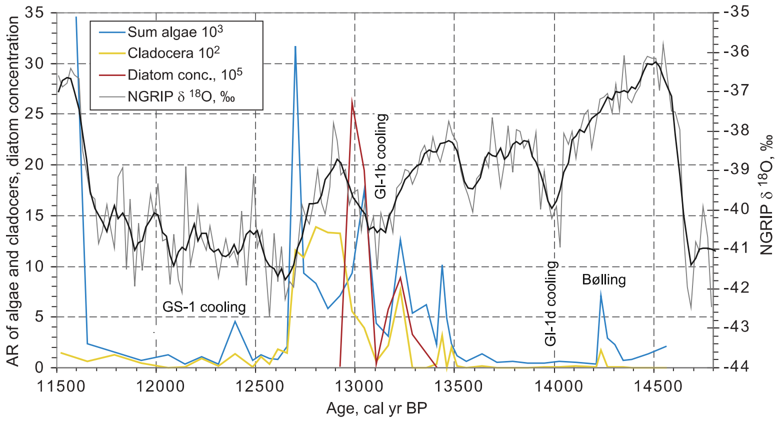

Fig. 8. Accumulation rates (AR) of green algae and cladocera as well as diatom concentration in the Lake Lielais Svētiņu sediment profile plotted against NGRIP $\delta^{18}O$ (‰) data (Rasmussen et al., 2006).

13,760 cal yr BP (in the LSM-4a subzone), the soil again became more favourable to telmatic species (*Menyanthes*), and *S. aizoides* disappeared. The pollen record of the post-Bølling cooling displays very low (under 300 grains cm^{-2} yr^{-1}) PARs for birch and pine for a period of 14,100–13,800 cal yr BP (Fig. 4), i.e., for a longer period than the cooling recorded in the NGRIP data (Lowe et al., 2008). The pollen corrosion is high (*Betula* 62%, total corrosion 70%), and the deviation from the mean ratio of dwarf birch versus birch pollen shows the highest positive anomalies, suggesting *B. nana* dominance in the local pollen rain (Fig. 6A). The corrected tree birch-type PAR for the GI-1d cooling in general are comparable to the earliest stages of the pioneer vegetation – below 200 grains cm^{-2} yr^{-1}. Before 13,800 cal yr BP, the deviation from the mean values of pine pollen degradation is negative, pointing to the non-local origin of *Pinus* pollen during GI-1d (Fig. 6B). The corrected *Pinus* PAR at approximately 350 grains cm^{-2} yr^{-1}, however, is higher than in previous periods and indicates a constant rise throughout the earlier part of the LG, thus suggesting an ever increasing pine pollen source in the south. Tree pollen (pine and birch) percentages and PARs gradually rise and at approximately 13,800 yr BP (the onset of the warmer GI-1c event), surpass the 500 grains cm^{-2} yr^{-1} limit (local presence *sensu* Hicks, 2001; Seppä and Hicks, 2006) and at 13,650 cal yr BP, surpass the 1000 grains cm^{-2} yr^{-1} (birch forest) limit. The conspicuous rise of tree PAR values in the middle of GI-1c, not concomitant with the warming seen in the NGRIP curve (Fig. 4) is explained by the relative delay in vegetation development due to the vicinity of the Scandinavian Ice Sheet and large proglacial lakes, similarly to the delay in Bølling when plants established only towards the end of the period. First, macrofossils of the tree/shrub birch *Betula humilis* appear at 13,680 cal yr BP, so the early open "birch forest" in reality might have been one-metre-high brushwood of dwarf and shrub birch. Approximately 200 years later, at 13,460 cal yr BP, *B. nana* suddenly disappears from the plant macrofossil record. At the same level, a tree birch section with *Betula* sect. *Albae* and *B. pubescens* is introduced, marking the start of a true tree birch forest in the area (Fig. 10). In Denmark, tree birch arrived earlier, at 13,600 cal yr BP, but pine did not arrive there until the Preboreal (Mortensen et al., 2011). At the same time, the PARs of *Pinus* and *Betula* reach over 2000 grains cm^{-2} yr^{-1}, and the *Betula* PARs reach a level of 4000 grains cm^{-2} yr^{-1} at 13,300 yr BP, remaining there until the Younger Dryas. Also, the corrosion percentages of birch pollen drop to 10%, indicating that most of the birch pollen was locally produced. The occurrence of numerous tree birch macroremains and high PARs confirm the presence of (tree) birch forests in eastern central Latvia, in the Lubana basin around Lake LS. Moist and telmatic conditions prevail around the lake, as

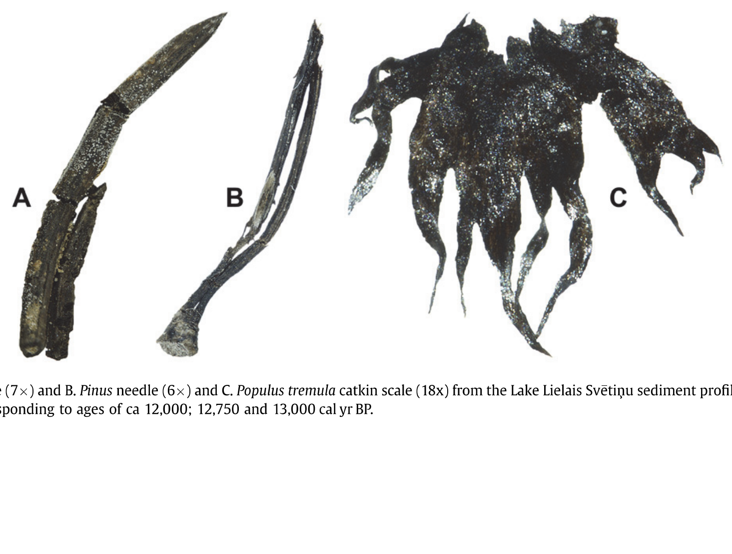

Fig. 9. Photos of A. *Picea* needle (7×) and B. *Pinus* needle (6×) and C. *Populus tremula* catkin scale (18x) from the Lake Lielais Svētiņu sediment profile at downcore sample depths of 1185, 1270 and 1290 cm, corresponding to ages of ca 12,000; 12,750 and 13,000 cal yr BP.

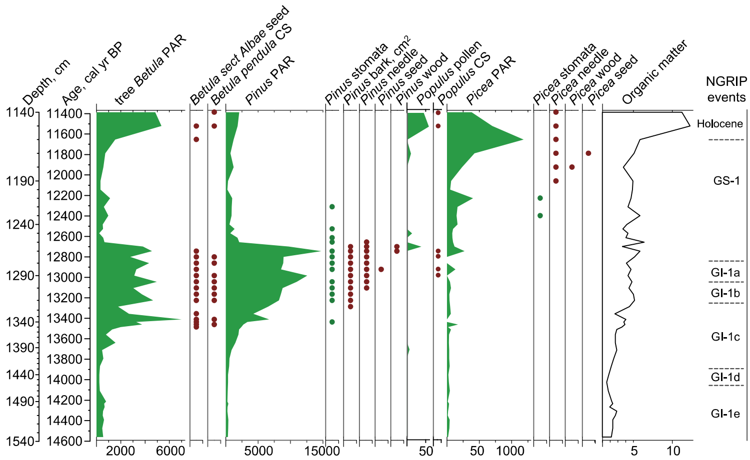

Fig. 10. Summary macrofossil and microfossil evidence of tree taxa in the Lake Lielais Svētiņu Lateglacial sediment profile.

macrofossils of *Juncus*, *Carex* and *Selaginella* are present as well as Bryales, *Sphagnum*, *Equisetum* and *Botrychium* spores and *Drepanocladus* leaf fragments in the pollen and spore record.

5.3. The Lateglacial forest at 13,300–12,700 cal yr BP (GI-1b and GI-1a)

The composition of plant macrofossils in zone LSM-5 (13,300–12,700 cal yr BP) demonstrates the effective introduction of *Pinus* and the formation of a mixed conifer forest. The presence of *Pinus* and pine forest is confirmed by a variety of macrofossils: bark, wood, needles, seeds (Fig. 9). Since the find of an unidentified conifer budscale at 13,400 cal yr BP, pine bark was identified since 13,300 cal yr BP and pine needles since 13,100 cal yr BP (Fig. 10). From the pollen signal, pine stomata are found prior to macrofossils, namely at 13,450 cal yr BP. The first pine stomata finds are associated with a *Pinus* PAR over 3000 and the pine macrofossil finds with a *Pinus* PAR over 4000 grains cm^{-2} yr^{-1}. The maximum pine PAR reaches far beyond 10,000 (14,000 in maximum) grains cm^{-2} yr^{-1} in the late Allerød, just before the Younger Dryas cold spell starts. Such high pine PAR seem surprising because just 140 km to the north, around Lake Nakri in southern Estonia, pine PAR seldom exceed 2000 grains cm^{-2} yr^{-1} level (Amon et al., 2012), and to date, no pine macrofossils are found north of LS in the eastern Baltic or, for instance, in Denmark, which is at an equal latitude with Latvia (Bennike et al., 2004a). These types of sharp ecotones were also present in Germany (Theuerkauf and Joosten, 2012). In addition to *Pinus*, deciduous trees formed a part of the forest community, namely birch (*B. pendula*) and aspen (*Populus tremula*). The find *P. tremula* catkin scales (Fig. 9) at 13,000–12,750 cal yr BP, during the warmest period of the GI-1a (Allerød) warming, makes it one of the few records of this plant species macrofossils in the LG period in Eurasia (Binney et al., 2009). Occasional pollen finds of *Populus* in the LG sediments of Lake LS do not coincide with the macrofossil data until the start of the Holocene. During GI-1a, the pollen grains of *Populus* are not found, probably due to the poor preservation of thin-walled pollen grains. Birch in the Allerød pine forest of eastern Latvia seems suppressed, with its PAR values of approximately 4000 grains cm^{-2} yr^{-1} during GI-1a. In south Estonia, birch is the only dominant tree, with recorded macrofossils and PAR over 4000 grains cm^{-2} yr^{-1} (Amon et al., 2012). The deviation of the *Betula*/*Betula nana*-type from the mean ratio (Fig. 6A) indicates negative anomalies, and *B. nana* macrofossils are missing from the record from 13,500 to 12,750 cal yr BP, indicating that tree birch was probably the main pollen producer.

At the local macrofossil scale, the growing conditions favour telmatic plants (*Juncus*, *Carex*, *Menyanthes*) instead of grasses and herbs (no remains found in this interval), which indicates that during the Allerød warm period, forest surrounded the lake from all sides and that the telmatic record comes from a narrow strip just around the lake shore. The void of NAP macrofossils is supported by low percentages of herbs in the pollen signal, though the PAR of NAP is high, indicating that pollen production in the warm period was favourable.

The GI-1a warm period was also beneficial for aquatic life, which responded to the climatic amelioration. The AR of green algae *Pediastrum*, *Tetraedron*, *Botryococcus* and *Scenedesmus* rises rapidly after 13,500 cal yr BP, and the algae thrive until 12,700 cal yr BP. The same can be said about Cladocera. In addition, a rather rich diatom flora was developed between 13,300 and 13,000 cal yr BP. In fact, this is the first time when diatoms are recorded in Estonian and Latvian LG sediments, and their evidence is used for palaeoenvironmental reconstructions. The infrequent occurrence of planktonic diatoms in the assemblage indicates a comparatively shallow limnic environment. Alternatively, the rarity of planktonic diatom species suggests rather cold winters, prolonged duration of the ice cover and a shorter growing season, which hampered the development of the phytoplankton community in the deeper water environment. The GI-1b (Gerzensee) cold event centred on 13,150 cal yr BP is recognised in the aquatic signal, but not in the terrestrial (pollen nor macrofossils). In Swiss lakes, the GI-1b oscillation occurs during a pine-dominated phase as well, and some authors (Lotter et al., 1992) argue that its vegetation effect cannot be determined palynologically. However, Wick (2000), based partly on the same material, shows a significant correlation between $\delta^{18}O$ and pollen for the Gerzensee oscillation. The 200 year cold period is reflected as a remarkable decrease in the AR of Cladocera remains, the AR of green algae (especially *Pediastrum* and *Scenedesmus*) and the diatom concentration in LS material. The life cycle of aquatic organisms in arctic lakes is dependent on climate related variables, such as the duration and extent of ice cover (Douglas and Smol, 1999). During the colder and longer winters at approximately 13,150 cal yr BP, a thick ice cover probably formed, which delayed the break-up of lake ice in the deeper areas, and only narrow areas in the littoral zone were ice-free. The intra-Allerød/

Gerzensee cold period GI-1b was detected as reduced cladocera concentrations in Bølling Sø (Bennike et al., 2004b; Sarmaja-Korjonen et al., 2006) and is well represented in the drop of tree pollen PARs in Lake Nakri, southern Estonia (Amon et al., 2012). One might argue that sites more northern and proximal to the ice edge, such as Nakri, are more sensitive for recording terrestrial vegetational shifts compared with fully established pine forests in central Latvia.

Heikkilä et al. (2009) found similar mixed conifer forests around Lake Kurjanovas in the 'Bølling/Allerød' interval. In their study, the mixed forest period started several hundred years earlier, ca 14,400–14,000 cal yr BP, when in areas around Lake LS in eastern Latvia treeless tundra conditions developing into birch forest prevailed. The earlier arrival of pine and the formation of dense forest in the Kurjanovas area may be tied to its south-easterly location. Lake LS is situated northeastwards from Lake Kurjanovas, i.e., to the direction of the deglaciation; the area in the southeast deglaciated earlier, and the state of environmental conditions was more developed and suitable for new species to migrate. The narrow transition zone from tundra to boreal forest might have been located between the Latgale upland and the eastern Latvian lowland by ca 14,000 (14,400) cal yr BP. The transition zone moved north-westwards, reaching the eastern Latvian lowland at ca 13,450 cal yr BP according to finds of pine stomata in Lake LS. Pine migrated further and perhaps had sparse colonies in southern Estonia at ca 13,300 cal yr BP (stomata evidence, Amon et al., 2012). However, the migration there stopped because at 13,200 cal yr BP, the ice front was still at the Palivere ice marginal zone in north Estonia (Saarse et al., 2012a,b), and treeless tundra conditions prevailed in northern Estonia until the Holocene warming (Amon and Saarse, 2010).

The surroundings of Lake Kurjanovas have a higher elevation compared with Lake LS, which might lead to drier soils that would be more suitable for pine compared with glacial lowland clayey soils. The 'Bølling/Allerød' interval of Lake Kurjanovas has been reported as a rather moist phase (Heikkilä et al., 2009), but the Lake LS sediments contain a variety of telmatic plant macrofossils from this period, except for a slightly drier interval at 13,900–13,600 cal yr BP. As an elevated area next to the upland, it was perhaps also better at trapping seeds from pine source areas southwards or southeastwards or even from the Latgale upland. In southeastern Lithuania, pine was also present at more than 14,000 cal yr BP (Stančikaitė et al., 2008) and in Belarus at the Allerød/Younger Dryas boundary (Makhnach et al., 2004).

A local sedimentological event took place inside the warmest part of the Allerød. The sediment composition changes in Lake LS at core depths of 1317–1332 cm (ca 13,300–13,200 cal yr BP), when a distinctly laminated (varved?) clay interval formed consisting of ca 20 varve couplets. MS increased, and OM content dropped remarkably. We can exclude the active glacier, which at that time was already in northern Estonia and the formation of laminated or varved clays was associated, most likely, with increased and seasonal mineral matter input from the melting of dead ice on the Latgale upland (Zelčs and Markots, 2004).

5.4. GS-1 Younger Dryas cold event (12,700–11,650 cal yr BP)

The last and most prominent 1000 year cooling event before the start of the Holocene warming, the GS-1 (Lowe et al., 2008), remarkably affected the floral composition in the Northern Hemisphere, including eastern Latvia. Around Lake LS, the forest species declined abruptly from a maximal PAR at 12,700 to a PAR below 1000 grains $cm^{-2}\,yr^{-1}$ at 12,600 cal yr BP, i.e., the response time for the pine forest to collapse was 100 years according to pollen accumulation data. Pine macrofossils disappear simultaneously with the pollen signal at 12,600 cal yr BP, yet occasional *Pinus* stomata are recorded throughout the GS-1. There is a growing body of evidence that boreal tree species survived and even sexually reproduced throughout Younger Dryas harsh conditions (Heikkilä et al., 2009, Binney et al., 2009; Väliranta et al., 2011) and the isolated patches of trees acted as initial nuclei for population expansion and forest development later, in the early Holocene. Aspen and birch plant macrofossils fade away earlier at 12,750 cal yr BP. The decline of birch PAR is more rapid compared with that of pine, which might explain the earlier disappearance of birch macrofossils. The landscape was altered to treeless shrub tundra once again. *D. octopetala*, *S. polaris* and *B. nana* are present in the macrofossil record accompanied with high percentages of *Juniperus* (20%), Poaceae, Cyperaceae and *Artemisia*. The NAP ratio compared with AP is positive from 12,600 to 11,650 cal yr BP, yet the landscape is not entirely treeless for the whole Younger Dryas, as pine and birch PARs drop below 500 grains $cm^{-2}\,yr^{-1}$ only for short periods at 12,600–12,500 and 12,200–11,900 cal yr BP. The time between these extreme cold spells (12,500–12,200 cal yr BP) is illustrated as rather suitable for OM sedimentation, with up to 8% of OM, i.e., LG maximal values occur. In that warmer window inside the cold Younger Dryas, *Picea* is introduced in the region and is represented by stomata (12,400–12,200 cal yr BP), needles, seeds and wood (since 12,050 cal yr BP up to the Holocene) (Figs. 9 and 10). *Picea* PAR surpasses the 100 grains $cm^{-2}\,yr^{-1}$ limit, which is the threshold PAR for the presence of spruce forest (Hicks, 2001), at already 12,750 cal yr BP, but only when the PAR occasionally exceeds 400 grains $cm^{-2}\,yr^{-1}$ do the spruce macrofossils and the pollen signal coincide. The LG presence of *Picea* in Latvia has been demonstrated by other studies (Heikkilä et al., 2009; Koff and Terasmaa, 2011). However, in these studies, the spruce was introduced slightly earlier, at 12,900 cal yr BP, according to pollen signals, and at 12,400 cal yr BP based on macrofossil evidence (Heikkilä et al., 2009). The easterly glacial refugium of spruce has been shown in numerous publications (Saarse et al., 1999; Giesecke and Bennett, 2004), and it is not surprising that spruce migrated to the eastern Baltic so early. By this time, the environmental conditions and climatic factors important for vegetation development that were connected with the ice retreat pattern had been stabilised and were more or less equal over mid-Latvia – the ice front was already in southern Finland. Therefore, more local and climatic factors that inhibited or favoured the migration of *Picea*, such as elevation (Lake Kuži 191.5 m a.s.l.), soil development, moisture regime, might have been more important. Again, the more easterly location of Lake Kurjanovas might have favoured earlier and stronger spruce invasion (Giesecke and Bennett, 2004). However, the occurrence of spruce during the LG is limited to mid- or eastern Latvia: in northern Latvia (Lake Burtinieks) *Picea* is absent in GS-1 (Ozola et al., 2010) as well as in Estonia (Saarse et al., 1999; Amon et al., 2010, 2012). The combination of fossil pollen and genetic data of *Picea abies* reveals the LG maximum refugium area in the Russian Plain that became the basis of the so-called northern lineage of present spruce in northern Europe (Giesecke and Bennett, 2004; Tollefsrud et al., 2008). The proposed area inhabited by the northern lineage of spruce in 10,000 cal yr BP extends from western European Russia to easternmost Latvia and the northernmost corner of Belarus, and it concentrically inhabits other areas.

5.5. Holocene warming and subsequent vegetation change

The Pleistocene/Holocene boundary at 11,650 cal yr BP is marked by changes both in vegetation composition and sediment type. The OM-rich gyttja accumulated instead of silts and clays, and the start of the Holocene warm period permitted forest re-expansion in the surroundings of Lake LS. Plant macrofossil data confirm the presence of mixed conifer forest (spruce, tree birch, aspen). *B. nana* disappears both from the pollen and macrofossil records, and typical early Preboreal open birch forest with spruce, junipers and willows developed.

6. Conclusions

The paper discusses a complete and unambiguous vegetation record since the Bølling warming from Lake Lielais Svētiņu in the Baltic area, NE Europe since 14,550 cal yr BP. Applying a novel method of corroded pollen combined with macrofossil data we separate the evidence of regional and local vegetation responses to LG climate. The results show that the GI-1e warming and the GI-1d cooling in the eastern Baltic area were treeless shrub tundra communities. With the onset of GI-1c warming at 13,500 cal yr BP *B. nana* macrofossils are replaced by tree birch *Betula* sect. *Albae*, marking the start of the forest phase. During the warmest period of the GI-1a, between 13,000 and 12,700 cal yr BP, a mixed pine forest with deciduous trees (birch – *B. pendula* and aspen – *P. tremula*) developed in the Baltic region. The Younger Dryas (GS-1) cooling strongly affected the forest in eastern Latvia, yet there is evidence that pine and spruce survived throughout the GS-1 harsh conditions. The Pleistocene/Holocene boundary at 11,650 cal yr BP is marked by forest re-expansion and changes in vegetation composition in eastern Latvia.

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Appendix. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.quascirev.2012.02.013

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Local and regional Holocene vegetation dynamics at two sites in eastern Latvia

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The study compares the local and regional Holocene vegetation dynamics of two sites in eastern Latvia. Both sites show similar trends in vegetation change. Differences were found in local abundances of *Betula*, *Pinus* and *Picea*. Lower amounts of *Betula* at the local site suggest stronger regional pollen influx into the regional site. The continuous presence of conifer stomata indicates the development of a stand-scale conifer forest at the local site since 5000 cal yr BP. Similar presence and dynamics in thermophilous tree species at both sites suggest that the pollen values of the regional site may truly show the local presence of thermophilous tree taxa. Apart from general vegetation succession, the strongest cause for the vegetation differences at both sites were water-level changes, as shown by the peat decomposition rate.

Introduction

Palaeoecological records preserved in sedimentary deposits provide a unique insight into the history of past ecosystems and long-term plant community dynamics. Although the postglacial vegetation history of Latvia has been studied for a long time (Galenieks 1935, Levkovskaya 1987, Kalnina *et al*. 2004), many postglacial sequences are still not dated and are described solely through comparisons of pollen zones; therefore, many questions still remain open, particularly regarding succession of regional and local vegetation. The main questions regarding the use of fossil pollen data are: (1) how credible are the results with regard to actual vegetation, and (2) what is the role of local *vs*. regional changes in vegetation dynamics? Smaller, stand-scale sites reflect better immediate changes in the vegetation than larger sites (Sugita 2007), where long-distance effects of pollen cannot be overlooked (Broström *et al*. 2008, Kuneš *et al*. 2008). Therefore, the comparison of two sites situated close to each other but with different pollen source areas may reflect differences between local and regional changes in vegetation dynamics.

The aim of this study was to compare local and regional Holocene vegetation dynamics in eastern Latvia. We analysed two adjacent sediment sequences and evaluated the vegetation dynamics in addition to possible factors controlling the development of vegetation at the local and regional sites.

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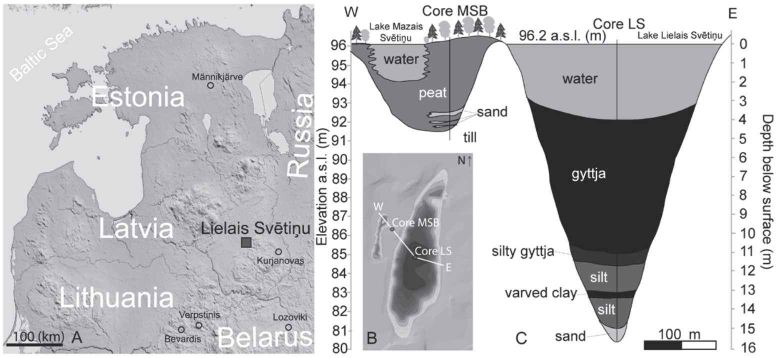

Fig. 1. (**A**) Map of the eastern Baltic area showing sites discussed in the text. (**B**) Location of the analysed sediment cores: Core LS, Lake Lielais Svētiņu; Core MSB, stand-scale site. (**C**) W–E sediment cross-section.

Study area

Lake Lielais Svētiņu (LS) (water depth 4 m; 56°45´N, 27°08´E) and the kettle-hole bog Mazais Svētiņu (MSB) (56°45´N, 27°08´E) are located in the Rēzekne district of eastern Latvia (Fig. 1) in the Lubāns lowland 13 km east of Lake Lubāns, and they are relics of an ancient large body of water (Seglins *et al*. 1999). The present-day topography was largely formed during the Weichselian glaciation and deglaciation (Zelčs and Markots 2004, Zelčs *et al*. 2011). The bedrock consists of Devonian dolomite covered by Quaternary deposits with a thickness of 5–10 m consisting of sand, silt and clay. LS is a drainage lake with an area of 18.8 ha, located at an elevation of 96.2 m above the sea level (a.s.l.). Its catchment (~12 km^2) is predominantly forested but also partly covered by fields. The flat shores of the lake are surrounded by *Betula*, *Picea*, and *Pinus* with scattered stands of *Ulmus*, *Tilia*, *Alnus* and *Quercus*. The radius of assumptive source area of pollen for LS is greater than 5 km, whereas MSB is a stand-scale site situated under a closed canopy of *Betula*, *Picea* and *Pinus*; therefore, its pollen source area is limited to 20–100 m (Overballe-Petersen and Bradshaw 2011).

The climate in the area is a combination of continental (Eurasia) and maritime (Atlantic Ocean); thus, the annual frequency of arctic and sub-polar air masses is fairly high (Draveniece 2009, Avotniece *et al*. 2010). The mean annual temperature of approximately the last 55 years in the closest city Rēzekne was +5.2 °C, with mean July and December temperatures of +16.9 °C and –4.1 °C, respectively (Dauškane *et al*. 2011).

Material and methods

Coring and lithostratigraphy

Sampling of sediments in LS (Fig. 1 and Table 1) was performed in March 2009 from ice using a Russian type corer with a diameter of 10 cm. The sediment thickness reached 1135 cm (the base of the core was 1550 cm below the surface of the water), of which the Holocene gyttja comprised 760 cm. Water depth of the lake was 400 cm. Multiple parallel overlapping sediment cores were documented, packed into film-wrapped 1-m plastic semi-tubes and transported to the laboratory for further analysis. The Holocene interval of the sediment core was examined for the present study. The lateglacial (LG) sequence of LS

Table 1. Lithostratigraphy of Lake Lielais Svētiņu.

Depth from water surface (cm)	Sediment description
400–1105	Gyttja, homogenous
1105–1160	Silty gyttja, homogenous
1160–1190	Silt with organic matter
1190–1270	Silt
1270–1320	Silt with organic matter
1320–1335	Clay, laminated
1335–1500	Silt, increasingly dark coloured from organic matter towards the upper limit
1500–1515	Sand with organic matter
1515–1535	Sand, compact

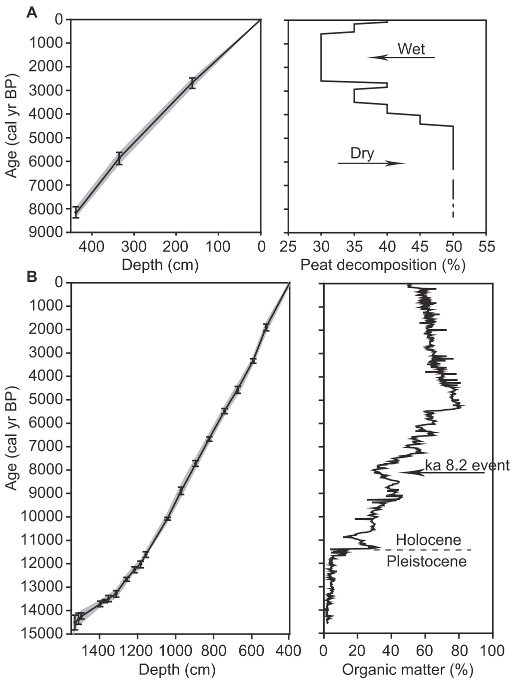

Fig. 2. (**A**) Mazais Svētiņu bog (MSB) age–depth model (bars indicate error of individual calibrated ages; shading shows the model uncertainty) and peat decomposition. (**B**) Lake Lielais Svētiņu (LS) age–depth model (bars indicate error of individual calibrated ages; shading shows the model uncertainty), and organic matter content.

was previously discussed in detail (Veski *et al*. 2012) and will be mentioned here only briefly. In October 2009, a 500-cm-long sediment sequence was taken from MSB using an Ejelkamp peat sampler with a 5-cm diameter and 50-cm length (Fig. 1 and Table 2); the sampling site is currently a stand-scale site beneath a closed canopy. The sampling procedure was performed as described above. The organic matter content of the LS sediment (Fig. 2) was determined by loss-on-ignition (LOI) at 550 °C for 4 h (Heiri *et al*. 2001). Measurements were performed on continuous 1-cm-thick subsamples, and LOI was calculated as a percentage of the dry weight. The degree of decomposition of the MSB peat (Fig. 2) was determined by the von Post pressing method (von Post 1924, Stanek and Silc 1977, Malterer *et al*. 1992) and centrifuging according to the Standard GOST 10650-71.

Table 2. Lithostratigraphy of Bog Mazais Svētiņu.

Depth from surface (cm)	Sediment description
0–5	*Sphagnum* peat
5–30	Wood-grass peat
30–155	Sedge peat
155–170	Wood-sedge peat
170–205	Wood-grass peat
205–360	Wood peat
360–375	Sand
375–410	Wood peat
410–420	Sand
420–425	Wood peat
425–435	Sand
435–450	Wood peat
450–500	Till

Chronology

The LS chronology was based on ^{14}C radiocarbon dates from 8 bulk (6-cm-thick) samples and 12 samples of terrestrial plant remains. The chronology of the MSB was based on conventional ^{14}C dating of three bulk (10-cm-thick) samples (Table 3). Macrofossils were radiocarbon-dated using the AMS method in the Poznań Radiocarbon Laboratory (Poz) in Poland, and bulk samples were dated by conventional liquid scintillation method at the Institute of Geology at Tallinn University of Technology (Tln) in Estonia. Radiocarbon dates were converted to calendar years using the IntCal09 calibration dataset (Reimer *et al*. 2004) and OxCal 4.2 programme deposition model (Bronk Ramsey 2001, 2008) with a two σ (95.4%) confidence level. The ages in the text refer to calendar years before present (cal yr BP; 0 = AD 1950).

Pollen analysis

Pollen subsamples (177 samples overall) of known volume (0.5–1 cm^3) and thickness (1 cm) were treated with 10% HCl, boiled in 10% KOH and then acetolysed for 5 min using standard acetolysis procedures (Berglund and Ralska-Jasiewiczowa 1986, Fægri and Iversen 1989) combined with cold concentrated HF treatment to remove inorganic matter (Bennett and Willis

2001). At least 500 terrestrial pollen and spores per sample were counted and identified to the lowest possible taxonomic level using the reference collection at the Institute of Geology at Tallinn University of Technology and published pollen keys. Although for both sites conifer stomata were identified according to Sweeney (2012), only for LS they were differentiated to *Pinus* and *Picea*; for MSB solely conifer stomata were registered. The percentage of dry-land taxa was calculated using arboreal (AP) and non-arboreal (NAP) pollen sums (excluding sporomorphs of aquatic and wetland plants). Counts of spores were calculated as percentages of the total sum of terrestrial pollen.

A pollen diagram was compiled using the TILIA 1.7.16 software (Grimm 2012), and zonation was performed according to the broken-stick model (Bennett 1996) based on binary splitting of the sum-of-squares method using the PSIMPOLL 4.27 software (Bennett 1992).

Results and discussion

Lithostratigraphy and chronology

The LS sediments (Fig. 2) in the lowermost portion from 1550 to 1160 cm consist of sand and silt with a thin layer of distinctly laminated clay, but the upper part from 1160 to 400 cm consists of silty gyttja and homogenous gyttja. The organic matter (OM) content fluctuated from 1550 to 1160 cm, but then sharply increased to 30% at 1160 cm. The OM content then increased to 82% at 750 cm and decreased to 50% at 400 cm.

The MSB sediment sequence (Fig. 2) was composed of wood peat from 450 to 205 cm with a few sand layers in the basal part from 434 to 427 cm, 419 to 410 cm and 373 to 359 cm. Further, continuous *Phragmites* wood peat (205–170 cm), *Phragmites* peat (170–155 cm), *Carex* peat (155–30 cm), *Carex–Sphagnum* peat

Table 3. Radiocarbon ages of Lake Lielais Svētiņu and Bog Mazais Svētiņu sediment.

Depth (cm)	Laboratory code	^{14}C date (yr BP)	Calibrated age (cal yr BP) 2σ	Model age (cal yr BP)	Material dated
Lake Lielais Svētiņu					
523	Tln-3167	1848 ± 70	2110–1725	1885	Bulk gyttja
593	Tln-3168	3231 ± 70	3480–3170	3350	Bulk gyttja
673	Tln-3169	4091 ± 70	4680–4420	4540	Bulk gyttja
743	Tln-3170	4701 ± 70	5590–5350	5490	Bulk gyttja
823	Tln-3171	5822 ± 90	6790–6500	6655	Bulk gyttja
893	Tln-3172	6876 ± 90	7840–7590	7720	Bulk gyttja
973	Tln-3173	7974 ± 90	9090–8730	8920	Bulk gyttja
1043	Tln-3174	9169 ± 100	10300–9900	10070	Bulk gyttja
1157	Poz-30426	10100 ± 60	11650–11590	11625	Wood
1185	Poz-36710	10270 ± 50	12140–11810	11990	Twig
1215	Poz-31768	10330 ± 50	12400–12120	12290	Wood
1261	Poz-31769	10760 ± 50	12760–12560	12660	Twig, bark
1315	Poz-36711	11460 ± 60	13400–13160	13290	Bark
1355	Poz-36712	11670 ± 60	13620–13400	13510	Stem
1365	Poz-36715	11630 ± 60	13660–13460	13560	*Betula nana* leaf, *Potentilla* seed
1400	Poz-36713	11840 ± 60	13830–13640	13740	Twig
1445	Poz-36714	12410 ± 60	14240–13990	14110	Twig, *Betula nana* leaf
1492	Poz-31770	12380 ± 60	14400–14040	14220	Twig, bark
1510	Poz-29298	12420 ± 60	14590–14150	14350	Wooden material
1530	Poz-31771	12350 ± 60	14950–14180	14520	Wooden material
Bog Mazais Svētiņu					
165	Tln-3202	2613 ± 60	2860–2490	2710	Bulk peat
335	Tln-3203	5154 ± 70	6180–5730	5900	Bulk peat
435	Tln-3205	7297 ± 100	8340–7950	8125	Bulk peat

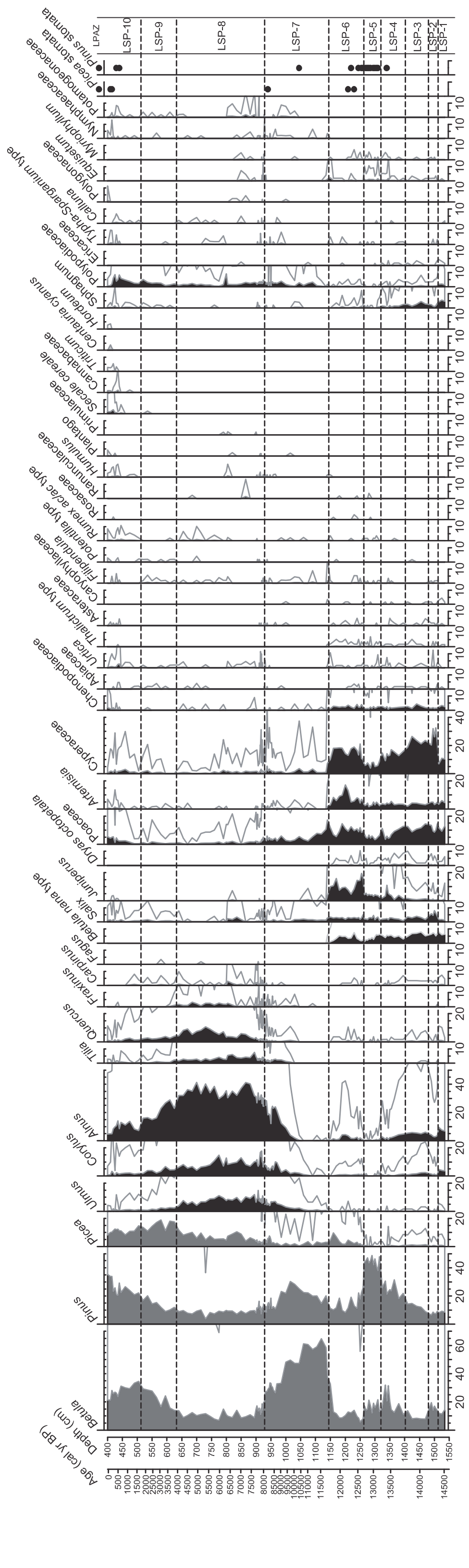

Fig. 3. Pollen diagram for Lake Lielais Svētiņu. Shaded line show ten-fold multiple abundance values.

(30–5 cm) and *Sphagnum* peat (5–0 cm) were observed. The peat was rather well decomposed (Fig. 2) between the depths of 450 cm (50%) and 205 cm (35%) and at a depth of 30 cm (40%).

The chronology of the studied sequences (Table 3) and age–depth models (Fig. 2) show that at LS the highest sediment accumulation rate of 0.16–0.17 cm^{-2} yr^{-1} was between 14 500 and 11 600 cal yr BP in LS. Later in the Holocene, the sedimentation rate was 0.06–0.08 cm^{-2} yr^{-1}. At MSB, a lower accumulation rate of 0.3–0.4 cm^{-2} yr^{-1} was found between 8300 and 6000 cal yr BP, and higher, 0.6 cm^{-2} yr^{-1}, after 4000 cal yr BP.

Pollen stratigraphy

The LG pollen diagram for LS was presented by Veski *et al*. (2012), and when combined with the Holocene pollen record it becomes the longest continuous documentation currently available for postglacial vegetal evolution in Latvia.

The pollen diagram for LS was divided into ten statistically significant, local-pollen-assemblage zones (LPAZ; Table 4 and Fig. 3) based on the broken-stick model using the PSIMPOLL 4.27 software (Bennett 1992). Core MSB pollen stratigraphy was divided into four statistically significant LPAZs (Table 5 and Fig. 4). Pollen taxa were selected to show similarities and differences for both sites.

Early Holocene (11 650–8000 cal yr BP)

The Holocene started at 11 650 cal yr BP (Lowe *et al*. 2008) with a rapid transition from cold to a generally warmer period. The early Holocene forests around LS were primarily dominated by *Betula* and *Pinus* (Table 4). In addition Heikkilä and Seppä (2010) point that the mean summer temperature of early Holocene was just 0.5 °C lower than reconstructed modern temperature from Lake Kurjanovas, eastern Latvia. The temperature controlled the duration of the growing seasons, and the shorter growing period favoured conifers over other species in the same overall climate and on similar soils (Ellenberg 2009).

The pattern of changes in the forest composition suggest that the conifer and *Betula* dominance started to weakened at the end of the early Holocene and later were suppressed by the thermophilous tree species. Similar pattern has been recorded in eastern Lithuania (Lake Verpstinis and Bevardis) (Gaidamavičius *et al*. 2011) and in northern Belarus (Lake Lozoviki) (Novik *et al*. 2010).

Table 4. Local pollen assemblage zones description of Lake Lielais Svētiņu.

Age (cal yr BP)	LPAZ	LPAZ description and vegetation type
1500–0 Late Holocene	LSP-10	Zone is dominated by arboreal pollen (AP). *Pinus* gradually increases from 30% to 40% at the end of zone. *Betula* decreases from 30% to 20%. *Picea* fluctuates between 8% and 15%. Decrease in broad-leaved trees. Increase of non-arboreal pollen (NAP); *Secale cereale* (2%), *Rumex* type (3%) peak; *Avena*, *Triticum, Cannabis* and *Hordeum* appear and have highest values. *Poaceae* increases from 1% to 5% at the end of zone. Polypodiaceae abundance up to 40%.
4000–1500 Late Holocene	LSP-9	*Betula* and *Pinus* values gradually increase in the upper part of the zone: *Betula* 10% in the first half of the zone, sharply increases to 30% in the end of the zone; *Pinus* increases from 10% to 20%. Highest values for *Picea* (17%). *Pinus* and *Picea* stomata are present. Slight decrease in all thermophilous tree species. *Alnus* decreases from 40% at the beginning of the zone to 15% at the end of the zone. *Fraxinus* first decreases to a minimum, and then it is not recorded in the second half of the zone. Polypodiaceae values rise from 5% in the first half of the zone to 22% at the end of the zone. *Secale cereale* and *Taraxacum* type appear at the end of the zone.
8000–4000 Middle Holocene	LSP-8	Thermophilous tree species dominate zone. *Fraxinus* (4%), *Tilia* (6%), *Corylus* (15%), *Ulmus* (10%), *Alnus* (40%) and *Quercus* (9%) have their maximum values. Throughout the zone, *Betula* and *Pinus* with low values, 10% and 8%, respectively. *Carpinus* values fluctuate (1%–3%) with a peak occurring at 6500 cal yr BP (3%). *Picea* values gradually increase from 3% to 10%. Poaceae values vary in the range 1%–2%. Polypodiaceae 5%–10% with a peak at 6300 cal yr BP (40%).
11 650–8000 Early Holocene	LSP-7	*Betula* values rise to 60%. *Pinus* values increase from 15% at the beginning of the zone to 30% in the middle of the zone, but afterwards decrease to 10%. *Pinus* and *Picea* stomata are recorded. *Juniperus* extinct. Thermophilous trees appear. *Ulmus* and *Corylus* occur since 11 200 cal yr BP but *Ulmus* values rise to 6% at 8500 cal yr BP, while those of *Corylus* to 10% at 8600 cal yr BP *Alnus* appears since 10 500 cal yr BP, and *Quercus* since 10 000 cal yr BP. *Picea* values are 1%–3%. *Artemisia* decreases to a minimum (1%). Poaceae decrease gradually (15% to 5%). All values of thermophilous tree species sharply fluctuate or decline but *Betula*, *Pinus* and *Picea* increase between 8300 and 8100 cal yr BP.
12 700–11 650 Younger Dryas	LSP-6	Open forest tundra with scattered *Betula*, *Pinus* and *Picea*. Tree types *Betula* and *Pinus* are less than 20%, *Picea* present as pollen and occasional stomata. *Juniperus* culmination (20%). NAP is represented by Cyperaceae, Poaceae, *Artemisia*, Chenopodiaceae, *Dryas octopetala*, *Thalictrum*.
13 300–12 700 Allerød warming	LSP-5	*Pinus*–*Betula* forest with a distinct dominance of *Pinus*. AP dominates reaching 70%. *Pinus* values over 50%, *Pinus* stomata are recorded, shrubs and NAP decrease.
13 760–13 300 Early Allerød	LSP-4	*Betula*–*Pinus* forest tundra. AP share gradually rises at the expense of NAP and around 13 600 cal yr BP exceeds it.
14 200–13 760 Older Dryas	LSP-3	NAP dominates over AP. In *Betula*/*Betula nana* relationship the later dominates.
14 400–14 000 Bølling	LSP-2	Herb/shrub tundra. *Betula* and *Pinus* are less than 20%, *Betula nana* and *Salix* are present. NAP is dominated by Cyperaceae, Poaceae and *Dryas* and *octopetala*.
14 560–14 400 Early Bølling	LSP-1	Treeless pioneer tundra. *Betula nana* type peaks. Poaceae values 10%.

Local and regional prevailing factors in vegetation history

To compare the local and regional dynamics of vegetation (Fig. 5), seven main tree species (*Picea*, *Pinus*, *Betula*, *Alnus*, *Ulmus*, *Tilia* and *Quercus*) were selected. Generally, both sites had consistent and comparable vegetation signals. Before 7500 cal yr BP, *Pinus* had constantly higher and *Alnus* constantly lower values at MSB than at LS. Therefore, other tree species were locally more dominant, but it can still be assumed that alder trees were part of the lake-rim vegetation. *Picea* had locally higher values at MSB than at LS, suggesting that during the early Holocene *Picea* locally replaced *Betula* as the dominant tree species. The lower local abundance of *Betula* suggests regional pollen loading at LS and regional transport (Dąbrowska 2008, Veriankaitė *et al*. 2010, Piotrowska and Kubik-Komar 2012). The local fluctuations of spruce and birch suggest changes in humidity and water table around the lake which can be supported by variation in peat decomposition rate (Fig. 2). The MSB values of *Quercus Ulmus* and *Tilia* were consistently comparable to those at LS and showed no local *vs*. regional differences, suggesting that the regional and local sites contained uniform shares of thermophilous trees. Surprisingly, *Pinus*, which is known for its high pollen productivity (Lisitsyna *et al*. 2011) and long-distance pollen loading (Ertl *et al*. 2012), had lower values at LS but was a dominant taxon at MSB. All of the compared tree species were natural components at both sites.

Although the vegetation dynamics at LS and MSB differed, it is possible to pinpoint some common trends, like changes from mixed *Pinus*–*Betula* forest to deciduous-temperate forest, and at the end to *Betula*–*Pinus*/human-induced changes in vegetation.

The dominance of *Betula*–*Pinus* from 8300 to 7500 cal yr BP suppressed other tree species locally. At MSB, the prevalence of *Alnus*, *Ulmus*, *Tilia* and *Quercus* was lower than at LS. Additionally, the increase in *Alnus* at MSB was shifted by 500 years relative to the increase in *Alnus* at LS, possibly because of the water level fluctuations and erosion of slopes supported by the presence of sand layers at the base of MSB (Fig. 2). Therefore, the pollen assemblage may have been contaminated by washed-out or redeposited pollen. Alternatively, the start of sedimentation at MSB and the low thermophilous tree pollen content may suggest a local-scale impact of the cooling well defined in the regional signal of LS. Wood peat accumulation and sedimentation disturbance by the sand layers agree with a cooling event at approximately 8200 cal yr BP (8.2 ka event). Within the expansion of thermophilous tree species, a sudden decline of the pollen values of all the broad-leaved taxa occurred at LS (Fig. 3), which

Table 5. Local pollen assemblage zones description of Bog Mazais Svētiņu.

Age (cal yr BP)	LPAZ	LPAZ description
1750–0 Late Holocene	MSB-4	NAP is dominated by Cyperaceae. Accompanied with Poaceae (5%), *Urtica* (4%), *Plantago* (6%), *Secale cereale* (2%) and *Cannabis* (2%). *Betula* constantly 10% with peak (55%) at the upper part of zone. *Picea* ca. 15% but decreases upwards. *Alnus* is present in low values. *Pinus* fluctuates between 10% and 20%. Reappearance of *Corylus*, *Ulmus*, *Quercus* and *Juniperus*. *Betula*–*Pinus* forest affected by human activities.
4600–1750 Late Holocene	MSB-3	*Alnus* values decrease from 40% to 10%. Strong dominance of Cyperaceae. Polypodiaceae and *Typha* maximum values (23%). *Picea* frequency varies between 10% and 35% and dominates together with *Pinus*. *Betula* is mostly around 10% with peak at ca. 4200 cal yr BP. *Betula*–*Pinus*–*Picea* forest.
7600–4600 Mid-Holocene	MSB-2	*Alnus* (40%), *Quercus* (15%), *Ulmus* (10%), *Corylus* (10%), *Tilia* (5%) and *Fraxinus* (4%) have their peak values. *Fraxinus* appears since 6500 cal yr BP. *Pinus* and *Betula* values below 15%. Mixed forest.
8300–7600 Mid-Holocene	MSB-1	AP dominated by *Pinus* and *Betula*. Among NAP, Poaceae, *Urtica*, Cyperaceae and *Artemisia* have higher values. Appearance of *Alnus*, *Quercus* and *Tilia*, but slight increase of *Picea* and *Ulmus*. Mixed forest.

is a reflection of the 8.2 ka event (Veski *et al*. 2004). The LS vegetation response to the 8.2 ka event was approximately 200 years long, and the OM of the LS sediments (Fig. 2) demonstrated a strong environmental disturbance for nearly 700 years. Hammarlund *et al*. (2003) performed an isotope $\delta^{18}O$ analysis of limnic carbonates at Igelsjön and found a decrease in the evaporation/inflow ratio during the summer that led to an increase in the lake level, whereas Hammarlund *et al*. (2005) detected cold and dry conditions during winters. An increase in the lake level caused increased catchment erosion and lead to a reduction of OM at LS, and sand layer accumulation in MSB sediments. Hede *et al*. (2010) found that increased $\delta^{16}C_{org}$ and algal pigment abundance strongly indicate erosional export of nutrients to Højby Sø in Denmark, thus leading to nutrient enrichment of the water column at approximately 8500–7900 cal yr BP. Although the reduction of OM in the sediments of Højby Sø lasted for approximately 250 years, after which it gradually decreased, parallel trajectories with small shifts in timing and duration were found for both LS and Højby Sø.

The middle Holocene between 8000 and 4000 cal yr BP marks the thermal maximum (HTM), which was characterised by a warm (~3.5 °C above the modern temperature), dry period (Birks and Seppä 2010, Heikkilä and Seppä 2010, Wanner *et al*. 2011) with reduced groundwater and lake levels (Hammarlund *et al*. 2003, Hammarlund *et al*. 2005, Sohar and Kalm 2008, Novik *et al*. 2010, Terasmaa 2011, Edvardsson *et al*. 2012). The expansion of thermophilous tree taxa at LS and MSB, and pollen-based temperature reconstructions from Lake Kurjanovas (Heikkilä and Seppä 2010) indicate that in eastern Latvia HTM occurred at 7500–5000 cal yr BP. The high peat decomposition at MSB (Fig. 2) supports this estimation of HTM and domination of dry and warm environmental conditions. During HTM, the soil and bog surfaces were warm and dry, which increased decomposition of fine, woody debris in temperate forests, and induced peat decomposition in bogs (Berbeco *et al*. 2012). The thermophilous forest expansion occurred between 7500 and 4500 cal yr BP at MSB, and between 8000 and 4000 cal yr BP at LS. Abundance of *Quercus* at

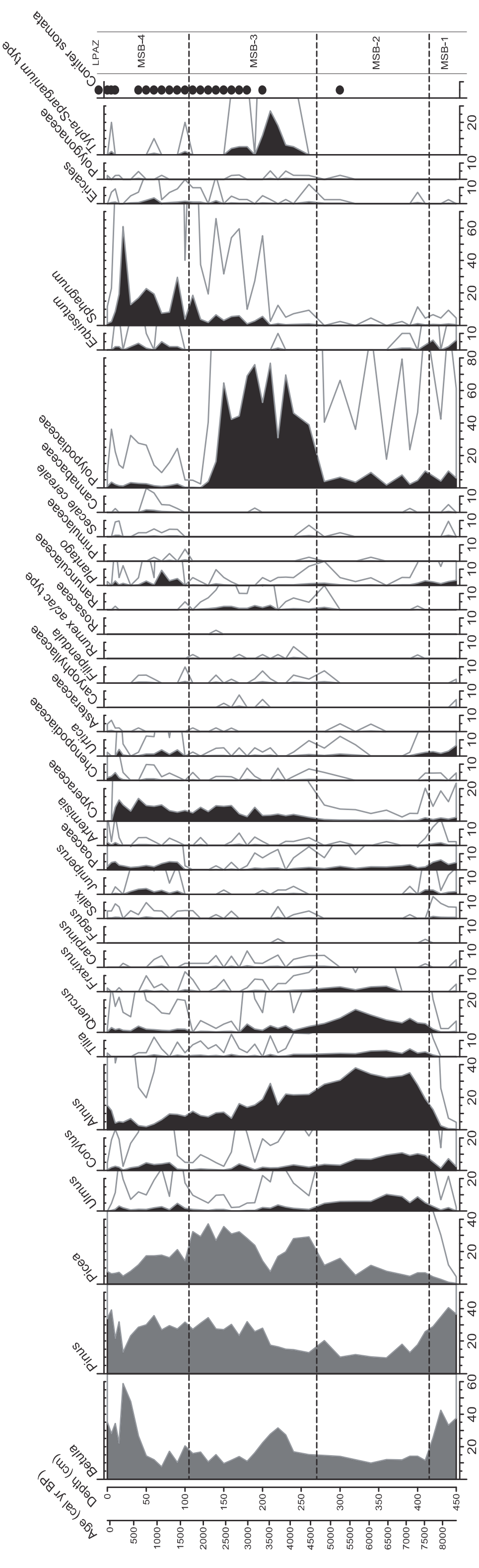

Fig. 4. Pollen diagram for Mazais Svētiņu bog. Shaded line show ten-fold multiple abundance values.

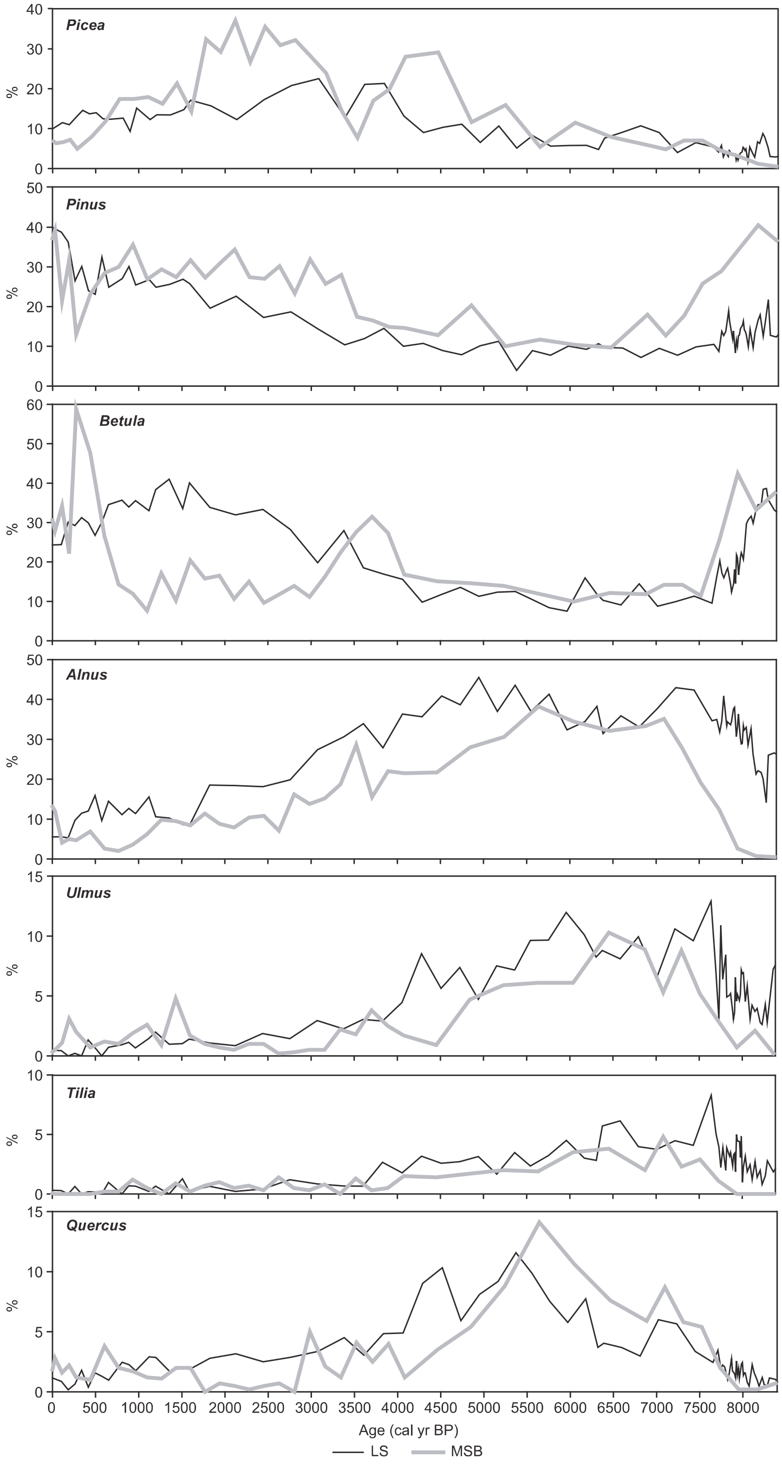

Fig. 5. Main tree pollen comparison of Lake Lielais Svētiņu (LS) and Mazais Svētiņu bog (MSB).

MSB suggests strictly local changes in the forest composition and availability of light. Although at the stand level *Quercus* can persist for multiple generations under a closed canopy, it has a wide-spreading crown, and it is thus a relatively light-demanding species that regenerates poorly in such conditions (Lindbladh and Foster 2010, Ikauniece *et al*. 2012).

The appearance and rapid increase in ferns (Polypodiaceae) at MSB (Fig. 4), and decrease in the peat decomposition rate (Fig. 2) since 4500 cal yr BP may indicate wetter conditions and an instant decline in thermophilous tree taxa even slightly earlier. In addition, the presence of *Picea* supports the existence of colder winters, moister soil and thicker snow cover (Giesecke and Bennett 2004). This change in environmental conditions matches the post-HTM cooler (Seppä and Poska 2004) and wetter (Hammarlund *et al*. 2003) phase previously shown at the regional level. Therefore, due to climate change strong difference between two sites appeared in transitional zone from HTM to post-HTM, i.e. from 4700 to 4000 cal yr BP. Whilst MSB showed reorganization in local-scale vegetation, LS still may have had possible regional pollen loading.

Starting at 3500 cal yr BP, MSB became an overgrown stand with a closed canopy composed of *Picea* and *Pinus*. The continuous presence of *Pinus* and/or *Picea* at MSB is supported by the finding of conifer stomata (Fig. 4). The presence of conifer stomata in the lake sediment or peat gives a reliable indication of local abundance of conifers within 20 m of the sampling location (Sweeney 2004, Parshall 1999). Bjune *et al*. (2009) indicated the usefulness of stand-scale site investigations because of their restricted pollen-source area, which can be directly linked to previous local vegetation. Therefore, the increase in *Pinus* and *Picea* pollen values at MSB indicates that a true local conifer forest was present and may have developed since 5000 cal yr BP, which is also supported by the findings of conifer stomata. In addition dissimilarity in values of *Picea* may represent local stands of *Picea* at MSB whilst the *Pinus* values at both sites showed similar trends. Development of the local stand-scale conifer forest may have been disrupted by an increase in the groundwater level. The expansion of *Typha–Sparganium* between 4000 and 3400 cal yr BP at MSB suggests wetter conditions and/or an increase in the groundwater level that caused *Picea* to decrease, thus making way for an increase in *Betula* and *Alnus*. Distinct vegetation changes were detected at MSB, whereas minor variation was found at LS. Therefore, the regional-scale site does not reveal all vegetation stress factors as well as the stand-scale site.

Although eastern Latvia has been inhabited by humans since the Mesolithic (Kalnina *et al*. 2004), human-induced vegetation changes with appearance of *Secale cereale*, Cannabaceae and increase in Poaceae at MSB came along around 1500 cal yr BP, which is nearly 1000 years earlier than the LS records suggests. Because of the generally forested and wet soil conditions, this area was inappropriate for early agriculture. The continuous presence of local forests in the vicinity from the establishment of terrestrial vegetation up to the present indicates that this area was unsuitable for early human land use before 1500 cal yr BP. Clear signs of landscape openness and human activity locally contrast with the LS records and suggest that human activity was minimal and/or local, and it primarily occurred near MSB. Differences in *Betula* pollen (Fig. 5) between the local and regional scales may be explained by differences in pollen sources, changes in soil properties or groundwater level fluctuation, which may be supported by the increase in *Sphagnum* and the low peat decomposition rate. The gap in conifer stomata from 600 to 200 cal yr BP may be attributed to increased wetness, which led to expansion of *Betula* as the main local-stand species. Sillasoo *et al*. (2007) studied *Testate amoebae* from the Männikjärve bog in Estonia and found a wetter phase since approximately 600 cal yr BP. The rapid drop in *Betula* and re-appearance of conifer stomata starting at 200 cal yr BP supports conifer and *Betula* co-domination around MSB and LS. A sudden change in water level may be responsible for these changes because of the start of ditching in the landscape, which is supported by an increase in peat decomposition at MSB and a decrease in OM at LS (Fig. 2). In addition to the fluctuation of the forest structure during the last 1500 cal yr BP, the decrease in OM also points to anthropogenic activities around MSB and LS. Human impact is supported by the increase in ruderal communities and cereals: *Urtica* since 1200, *Rumex acetosa*/*acetosella*-type since 1500, *Avena* since 200, *Secale cereale* since 600, *Triticum* since 500, *Hordeum* since 150 and *Cannabis* since 600 cal yr BP. Given the relatively late human-induced disturbance of MSB and LS sediments, this area appears to have been primarily affected by natural climate and environmental variability.

Conclusions

A comparison of local and regional pollen evidence obtained from two adjacent sites suggests comparable vegetation trends at local and regional sites. The local site showed higher abundance of conifers. Conifer stomata show that conifers (pine and spruce) were present and co-dominant in the vicinity as a stand-scale forest starting at 5000 cal yr BP with a gap at approximately 500 cal yr BP, when other taxa dominated. Lower pollen values at the local site suggest that the prevalence of birch was somewhat overestimated at the regional site in the period 3500–500 cal yr BP. Consistent abundance of *Quercus*, *Ulmus* and *Tilia* over time suggests that their pollen found regionally may actually represent their stable presence.

Local environmental conditions and regional to supraregional events can be seen as the main reasons for vegetation fluctuation and differences in local and regional vegetation dynamics. The stand-scale site experienced greater impacts and reacted stronger to different types of stress factors (mostly ground and lake water level changes and temperature) than the regional site; however, the two data sets were surprisingly similar.

Ditching in the landscape has increased the peat decomposition rate and reduced the ground water and lake water level in recent years, which is one of the main factors for the disturbance of the local vegetation dynamic. Human activities in this area such as land use and clearance of the landscape started 1500 cal yr BP. Therefore, given the relatively late timing of human-induced disturbance, this LS presents natural vegetation dynamic.

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ORIGINAL ARTICLE

Landscape change in central Latvia since the Iron Age: multi-proxy analysis of the vegetation impact of conflict, colonization and economic expansion during the last 2,000 years

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Abstract This study represents the first detailed multi-proxy palaeoenvironmental investigation associated with a Late Iron Age lake-dwelling site in the eastern Baltic. The main objective was to reconstruct the environmental and vegetation dynamics associated with the establishment of the lake-dwelling and land-use during the last 2,000 years. A lacustrine sediment core located adjacent to a Late Iron Age lake-dwelling, medieval castle and Post-medieval manor was sampled in Lake Āraiši. The core was dated using spheroidal fly-ash particles and radiocarbon dating, and analysed in terms of pollen, non-pollen palynomorphs, diatoms, loss-on-ignition, magnetic susceptibility and element geochemistry. Associations between pollen and other proxies were statistically tested. During AD 1–700, the vicinity of Lake Āraiši was covered by forests and human activities were only small-scale with the first appearance of cereal pollen (*Triticum* and *Secale cereale*) after AD 400. The most significant changes in vegetation and environment occurred with the establishment of the lake-dwelling around AD 780 when the immediate surroundings of the lake were cleared for agriculture, and within the lake there were increased nutrient levels. The highest accumulation rates of coprophilous fungi coincide with the occupation of the lake-dwelling from AD 780–1050, indicating that parts of the dwelling functioned as byres for livestock. The conquest of tribal lands during the crusades resulted in changes to the ownership, administration and organisation of the land, but our results indicate that the form and type of agriculture and land-use continued much as it had during the preceding Late Iron Age.

Keywords Lake-dwelling · Pollen · Non-pollen palynomorphs · Late Iron Age · Crusades · Latvia

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Introduction

The cultural phenomenon of lake-dwellings occurred throughout Europe since the Neolithic (Forste 2012) expanding in the Alpine region (Leuzinger and Rast-Eicher 2011; Menotti 2003, 2004), France (Magny et al. 2012), Britain (Bulleid and Grey 1911; Coles and Coles 1989), Sweden (Göransson 2002), Slovenia (Jeraj et al. 2009), Belarus and western Russia (Mikljaev et al. 1984), Lithuania (Menotti et al. 2005; Motuzaitė-Matuzevičiūtė 2008; Pollmann 2014; Pranckėnaitė 2014) and Estonia (Ilves 2010; Kriiska and Roio 2011). The lake-dwelling culture spread into present-day Latvia in the Late Iron Age (Apals 2012; von Sievers 1876), while it was already in decline in the rest of Europe (Giachi et al. 2010; Jacomet 2009; Magny et al. 2012; Menotti 2003; Motuzaitė-Matuzevičiūtė 2008; Tolar et al. 2011). Ten lake-dwelling sites of approximately the same age have been found in Latvia (Fig. 1) (Apals 2012). One of the most important lake dwelling sites is Araisi (Āraiši or Āraišu in Latvian) (Apals 2002) which is one of the best studied hydro-

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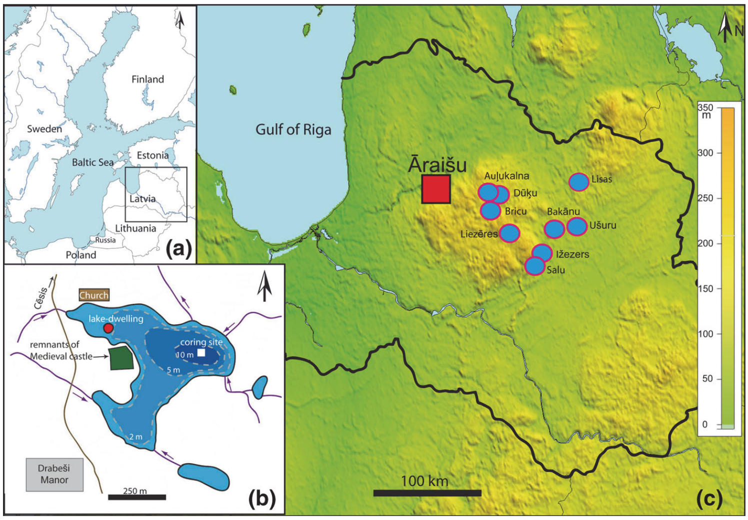


Fig. 1 Study area: **a** location of study site in eastern Baltic area; **b** Lake Araisi (Āraišu in Latvian) and other lakes where dwelling sites has been found in central Latvia; **c** coring site and setting around the Lake Araisi

archaeological sites in the Baltic region. Archaeological excavation took place from 1965 to 1979 and the finds reveal a community who lived permanently on the lake and engaged in farming, beekeeping, craft and trading activities. Radiocarbon wiggle-matching implies that the fortified lake-dwelling was built in ca. AD 780 (Meadows and Zunde 2014).

Despite the singularity of lake-dwelling sites, there have been few or no detailed palaeoecological studies aimed at understanding their environmental context and impact on the landscape. The aim of our study is to fill that gap and provide a detailed multi-proxy palaeoenvironmental investigation of the Araisi lake-dwelling site with a specific focus on reconstructing the environmental and vegetation dynamics during the occupation of the dwelling. In addition, Lake Araisi is uniquely placed to assess the comparative impact of human settlement over successive periods because in addition to the lake-dwelling, there is a medieval castle and a Post-medieval manor in close vicinity to the lake. The Late Iron Age, medieval and Post-medieval periods are times of significant cultural, social, political and economic change that have traditionally been investigated through archaeological and historical sources, and rarely using palaeoecological techniques. By taking a long-term approach offered by the palaeoenvironmental record, it will be possible to place the lake-dwelling in a broader environmental, cultural and historical context, and consider the extent of influence that local settlements had on the surrounding landscape. Of particular interest are the potential changes in vegetation and land-use related to the time between the abandonment of the lake-dwelling and the crusades during the early 13th century. Did people continue to settle the landscape surrounding the lake despite the abandonment of the lake-dwelling? As archaeological evidence from the castle suggests a rather low level of activity during the medieval period, it is also interesting to consider the broader ecological impact of the crusades and the subsequent administration by the Livonian Order. Moreover, what are the human-induced changes, if any, during the Post-medieval period? How do the past human-induced ecological changes compare to more recent evidence of human activities, particularly the excavation of the lake-dwelling, which involved a drastic lowering of the lake level.

Study site

Lake Araisi is located (57° 15´N, 25° 17´E) in central Latvia (Fig. 1), on the western edge of the Vidzeme Upland, 6 km south of Cēsis at an elevation of 120.2 m above sea level. The area of the lake is 32.6 ha, it has a flow-through hydrological regime and a mean and maximum depth of 4 and 12.3 m, respectively. The size of the lake's catchment area is ~10 km^2 and the surrounding hilly landscape is predominantly open fields and meadows. The shores are flat except for the east-south shore which is steep, surrounded by scattered stands of *Alnus incana*/*glutinosa*, *Betula pendula*/*pubescens*, *Picea abies*, *Pinus sylvestris* and *Quercus robur*. The present-day topography

Fig. 2 Aerial photograph of the western part of the Araisi Lake with a reconstructed fortified lake-dwelling of Araisi (photograph by Aigars Briune)

was formed largely during the Weichselian glaciation and deglaciation (Zelčs and Markots 2004; Zelčs et al. 2011). The geology is Devonian sandstone overlain by 80 m of till. The climate is characterized as continental; the mean annual precipitation is 700–800 mm, with mean temperatures of −6 °C in January and +16.5 °C in July.

Archaeological setting

The publication of Carl Georg von Sievers' "Pfahlbau im Arrasch-See (Lievland)" in 1876 pointed to the possible existence of lake-dwelling sites in Latvia (von Sievers 1876). During the 1960s, the pioneering underwater archaeologist Jānis Apals and his research team discovered ten lake-dwelling sites in Latvia (Fig. 1) (Apals 1960; Apals 2012; Meadows and Zunde 2014). Large-scale archaeological excavations of the Araisi fortified lake-dwelling took place in 1965–1979 identifying five building layers containing artefacts belonging to the culture of Late Iron Age Latgallian tribes (Apals 2002, 2012). Archaeological data suggest that the fortified lake-dwelling was inhabited in the ninth and tenth centuries— i.e. in the Late Iron Age. Recent radiocarbon wiggle-matching demonstrates that the lake-dwelling was built in ca. AD 780 (Meadows and Zunde 2014). Radiocarbon dates (all age data in the following are years AD) suggest that the site was occupied until the mid-tenth century (Apals 2012). Between AD 1208 and 1227 the Latgallian territory was conquered by the Order of the Brothers of the Sword (later to become the Livonian branch of the Teutonic Order) as part of a broader crusade across the eastern and south-eastern Baltic that sought to convert the Pagan tribes to Christianity (Urban 2003; Pluskowski 2012). The crusades led to the imposition of new political and religious institutions, the foundation of towns (e.g. Riga) and economic intensification, notably the development of the Hanseatic League. The castle at Araisi was constructed during the first half of the 14th century (Caune and Ose 2004) three centuries after occupation of the lake-dwelling had ceased. The presence of an Order Castle on the lake shore (Fig. 1) only 6 km from the headquarters of the Livonian Order at Cēsis, suggest that this area was strategically important during the medieval period. The castle was in use until the 17th century, in its final phase as a manor (Apals 1996; Pluskowski pers. comm. 2013). On the opposite shore of the lake, there is a parish church (Fig. 1) which has been destroyed and rebuilt several times. At present, the lake-dwelling is reconstructed (Fig. 2) and serves as an archaeological open-air museum.

Materials and methods

A 12.4 m-long sediment sequence was recovered at the deepest point of the lake (12.3 m) with a 1 m-long Russian type corer from the ice-covered lake surface in March 2012. The topmost 0.5 m of unconsolidated sediment was sampled using a Willner-type gravity corer. Sediment cores were documented, packed into film-wrapped one metre plastic PVC semi-tubes. The topmost sediment sequence was sub-sampled into 1-cm slices, put in plastic bags and transported to the laboratory for further analysis.

Continuous 2-cm thick sub-samples were combusted at 550 °C for 4 h to determine the organic matter content of the sediment and the ignition residue was estimated as the mineral matter (MM) content of the sediment. Magnetic susceptibility (MS) was measured with a Bartington MS2E meter (Nowaczyk 2001).

Pollen sub-samples (36 samples covering the last 2,000 years or 465 cm of sediment) of known volume (1 cm^3) and thickness (1 cm) were treated using standard acetolysis procedures (Berglund and Ralska-Jasiewiczowa 1986; Fægri and Iversen 1989). Known amounts of *Lycopodium* spores (University of Lund) were added to the samples to calculate pollen/spore concentrations and accumulation rates (AR) (Stockmarr 1971; Chambers et al. 2011) and mounted in glycerol (Erdtman 1969; Cushing 2011). More than 900 (except for one sample with 837) terrestrial pollen grains per sample were counted to the lowest possible taxonomic level using the reference collection at the Institute of Geology at Tallinn University of Technology and a published pollen key (Fægri and Iversen 1989). The percentage of dry-land taxa was calculated using arboreal and non-arboreal (NAP) pollen sums (excluding sporomorphs of aquatic and wetland plants). Counts of spores were calculated as percentages of the total sum of terrestrial pollen. A pollen diagram was compiled using TILIA 1.7.16 software (Grimm 2011). The pollen diagram and all fossil proxy data were subdivided in four zones according to archaeological periods (Graudonis 2001).

A wide group of other microfossils—non-pollen palynomorphs (NPPs) (van Geel 2001)—were recorded alongside pollen and identified using published literature on NPPs (Macdonald 2001; Sweeney 2004; Jankovská and Komárek 2000; Marrotte et al. 2012; Chmura et al. 2006; van Geel 2001; van Geel and Aptroot 2006; Korhola and Rautio 2001; Walker 2001; Bellinger and Sigee 2010; Komárek and Jankovská 2001). Algae were combined to general groups such as Cyanobacteria (*Anabaena*, *Aphanizomenon*, *Rivularia*, *Gloeotrichia pisum*, *G. natans*-type), *Botryococcus* (*B. pila*, *B. braunii*, *B. neglectus*), *Scenedesmus* (*S. quadricauda*, *S. obliguus*, *S. aecuatus*, *S. opaliensis*) and *Pediastrum* (*P. boryanum* var. *boryanum*, *P. boryanum* var. *cornutum* etc.). NPPs were expressed as AR (Wood and Wilmshurst 2013).

Diatoms were analysed at 23 stratigraphic levels, each subsample being 0.5 cm^3. Diatom samples were digested in hydrogen peroxide according to Battarbee et al. (2001). Diatom taxonomy was based primarily on Krammer and Lange-Bertalot (1986–1991). Small-size benthic fragilarioid diatoms were amalgamated into one group. Only selected diatoms (*Aulacoseira ambigua*, *A. subarctica*, *Cyclotella comta*, *Stephanodiscus parvus* and small-sized *Fragilaria* spp.) indicating natural conditions or related to human activities were included in statistical analysis.

Element concentrations were determined for 18 elements using Inductively Coupled-Optical Emission Spectroscopy (ICP-OES). In order to look at sedimentation history and human impact, a wide range of elements was analysed. Some elemental enrichment, such as Potassium (K) (Holliday and Gartner 2007) and Lead (Pb) (Cook et al. 2010; Hutson and Terry 2006) are known to be strongly associated with anthropogenic activities. Some elements, such as Calcium (Ca) and Titanium (Ti) (Lomas-Clarke and Barber 2007; O'Connell et al. 2013) are known to be associated with precipitation, sedimentation and erosion processes. Oven-dried sediment samples from Lake Araisi were pre-treated by nitric acid digestion and analysed with soil and element standards and blanks analysed alongside using a Perkin Elmer Optima 7300 DV ICP-OES. Element analysis was carried out to emphasize the impact of lake-dwelling and crusades; therefore it covered a specific time period (AD 300–1700) and not the whole study period. Geochemical concentrations were expressed as parts per million (ppm) per 0.5 g of dried sediment.

The chronology was based on ^{14}C radiocarbon dates from 7 bulk (5 cm-thick) sediment samples and for the upper sequence by distribution of spheroidal fly-ash particles (Heinsalu and Alliksaar 2009; Rose 1990). Samples were dated by a conventional liquid scintillation method at the Institute of Geology at Tallinn University of Technology (Tln) in Estonia. Radiocarbon dates were converted to calendar years using the IntCal13 calibration dataset (Reimer et al. 2013) and Clam 2.2 programme deposition model (Blaauw 2010) with a 95.4 % confidence level. Based on chronology sediment accumulation rate was estimated for each cm.

Statistical analysis

We used the R environment (version 3.1.1) (R Core Team 2014) for all statistical analyses. To characterize the general trends in terrestrial vegetation change, unconstrained ordination of pollen data was used– namely the principal components analysis (PCA) on the covariance matrix of the Hellinger-transformed pollen percentages. This transformation allows analysis of community data using Euclidean distance based ordination methods (like PCA) offering a preferable alternative to Chi square distance based ordination methods (Legendre and Gallagher 2001). To evaluate the significances of the PCA axes, we used the broken stick method (Legendre and Legendre 1998).

To illustrate community change through time, we superimposed the time-trajectory on the PCA plot. To investigate the associations between pollen data and other proxies, we used the "envfit" function from R package vegan (Oksanen et al. 2013). The envfit function fits the proxy data onto the previously calculated pollen ordination identifying the gradients in pollen data related to the other proxies without constraining the pollen-based ordination.

Table 1 Radiocarbon ages of Lake Araisi sediment

Depth, (cm)	Lab. code	^{14}C date, (years BP)	Age, cal years BP (2σ range)	Modelled age	Material dated
1,373	Tln3308	684 ± 95	520–785	AD 1330	Bulk
1,423	Tln3309	943 ± 105	680–1,020	AD 1095	Bulk
1,473	Tln3310	1,106 ± 95	900–1,260	AD 920	Bulk
1,523	Tln3311	1,280 ± 110	970–1,370	AD 780	Bulk
1,573	Tln3316	1,365 ± 60	1,175–1,380	AD 650	Bulk
1,623	Tln3317	1,636 ± 65	1,640–1,695	AD 440	Bulk
1,673	Tln3318	1,843 ± 70	1,605–1,930	AD 150	Bulk
1,723	Tln3312	2,163 ± 75	1,995–2,335	210 BC	Bulk

The significances of associations between the ordination and the proxy data were assessed using Monte Carlo permutations (1,000 permutations). Not all proxies were sampled exactly at the same depths/time points as the pollen data and in order to perform the envfit analysis, we first used local regression (LOESS) to predict proxy data values in the time points with pollen data.

The element concentration analysis did not cover the whole time-span of the pollen data-set and therefore we were unable to use the envfit function on the element concentration dataset. In order to examine the associations between the pollen data and the element concentrations, we used correlation analysis (Pearson's product-moment correlations) between the first two PCA axes and the element concentrations for the time-span where we had both pollen and element data (AD 300–1700).

In addition, we used palynological richness to characterize pollen data. Palynological richness was calculated with the help of the rarefaction analysis (Birks and Line 1992) where the pollen counts where standardized to the minimum pollen sum of 837– E(T_{837}).

Results

Lithostratigraphy, chronology and geochemistry

Altogether 1,240 cm of sediment was obtained, but only the uppermost 460 cm of gyttja covering the last 2,000 years was examined for the present study (Table 1; Fig. 3). The peak in spheroidal fly-ash particles at depth 35 cm was attributed to 1970, MM content was roughly 50 % from AD 1–750 (Table 2; Fig. 7), rapidly increasing by 15 % from AD 750, with MM content remaining high (65–78 %) until AD 1980. The chronology of the studied sequence and age-depth model show that the average sediment accumulation rate was 0.17 cm year^{-1} until AD 700, 0.35 cm year^{-1} from AD 700 to 1100 and 0.2 cm year^{-1} from AD 1100 to 1300, and again 0.17 cm year^{-1} until AD 1800 when it rose up to 0.25 cm year^{-1} in the upper part of the sediment sequence.

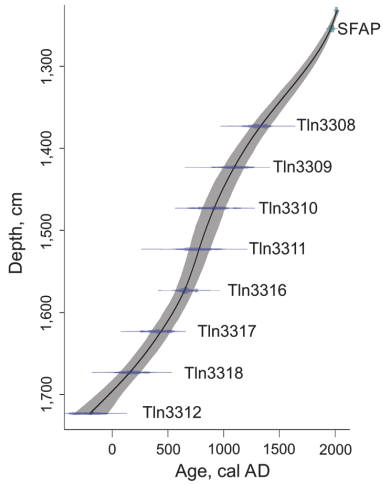


Fig. 3 Age-depth model for Lake Araisi sediment sequence (*grey area* indicates a reconstructed 95 % chronological uncertainty band)

Geochemical components indicate low Lead (Pb), Strontium (Sr) and Calcium (Ca) values during the Early Iron Age (ESM 1). Cadmium (Cd) had relatively higher values during the Early Iron Age comparing to the Middle Iron Age. At the end of the Middle Iron Age, starting from AD 750, Pb, Cobalt (Co), Chromium (Cr), Titanium (Ti) and Vanadium (V) increased. Pb continued to rise since then, reaching its highest point at AD 1700. Other elements showed fluctuating values from AD 300 to 1700. Several elements like Ca, Cr, Magnesium (Mg), Na, Phosphorus (P), Sr and Zinc (Zn) had peaks within AD 1250–1300.

Pollen, algae and other non-pollen palynomorphs

Early Iron Age (AD 1–400)

The pollen record shows that the vicinity of Lake Araisi was covered by forests during the Early Iron Age (Fig. 4). There were no finds of cereal grains during this period and

Table 2 Zones and description of archaeological, sedimentary, terrestrial and aquatic evidence

Age, AD	Archaeological evidence	Sedimentary evidence	Terrestrial evidence	Aquatic evidence
1200-2012 Hist, times	Archaeological excavation; Manor; Cemetery; Parish; Medieval castle; Crusaders	High MM content; peak at 1970. MS highest values ca. 1300-1450 and 1800-1960. High values of Cd and Pb from 1620-1700 and peak of P at 1675	Intensive agriculture with a peak of *Secale cereale* and *Centaurea cyanus* at 1800 and decrease towards present-day. Scarce tree stands in vicinity. Increase of charcoal	Deep lake with mesoeutrophic in-lake productivity and significant variations in diatom, green algae and cyanobacteria abundance and composition. Since 1950s increase of *Stephanodiscus parvus* shows distinct nutrient loading
800-1200 LIA	Lake-dwelling; Finds attributed to the culture of Latgallians; Dirham coins	High MM with a peak at 950-1000. MS values rise from 800 to 1000, decreasing thereafter. Low to medium level of P; medium to high of Cd, Co, Cr, Ti, Mg and V	Semi open landscape dominated by cultivated land, meadows and pastures. Rise of Poaceae to almost 10%. Charcoal peak at 1050. The highest AR of the coprophilous fungi and *Glomus* from 750-1050	Blooms of cyanobacteria, cladocerans and *Scene-desmus* and *Pediastrum* show in-lake nutrient enrichment. High abundance of planktonic diatom *Aulacoseira ambigua* suggests higher turbulence and mixing of the water column
400-800 MIA	Worship place of the Semigallians culture 1.3 km to E	Moderate MM values until 750 when then dramatically increase. Low MS (-1-0.5 κ). Low level of Ni and Pb, but medium to high level of Cd and P	Forest with increasing landscape openness. Appearance of the first clear cultivated land taxa *{Triticum* and *S. cereale),* beginning of intensive land-use since 750. Increase in fungi hyphae and charcoal, variable expansion of coprophilous fungi; significant amount of *Picea* stomata. Strong *Alnus* decline starting from 400 -700	High abundance of cyanobacteria and eutrophic planktonic diatom *Stephanodiscus parvus* and in-crease of small-sized fragilarioid taxa indicate in-lake nutrient enrichment
1-400 EIA	Stray-find of brooch and bracelet; settlement and iron smelting places 1 km to NW	MM content - medium (50-55%); low values of MS. Low level of Ni and Pb; medium of Ti, V, Mg;highofPandCd	Predominantly wooded with scarce presence of ruderal and pasture plants. Low but per-manent presence of coprophilous fungi	Rather stable assemblage of phytoplankton indicat-ing mesoeutrophic conditions. Increase of cyano-bacteria and appearance of eutrophic diatom *Stephanodiscus parvus* at 350

constantly low values of herbs were recorded. AR of Cyanobacteria, *Botryococcus* and *Pediastrum* stay low throughout the Early Iron Age (Fig. 5). Only seven types of fungi were recorded and the highest AR were recorded of *Kretzschmaria deusta*.

Middle Iron Age (AD 400–800)

Betula reached its highest percentage values around AD 400–500 and *Alnus* declined with values as low as 5 % from AD 400 to 700. The appearance of *Secale cereale* and *Triticum* from AD 400 along with several taxa of ruderal communities indicates the establishment of cultivation. The AR of *Secale cereale* showed an abrupt increase with pollen grains above 1,000 cm^{-2} year^{-1} around AD 750 (Fig. 7e). An increase in diatoms of *Stephanodiscus parvus* (20 %) indicates the eutrophication of the lake (Fig. 5). Charcoal AR increased after AD 750 (Fig. 5). Moreover *Sordaria*, *Sporormiella* and *Glomus* spores increased abruptly after AD 750 (Fig. 5). *Sordaria* and *Sporormiella* are known as coprophilous or dung fungi and indicate livestock presence in vicinity (Baker et al. 2013). *Glomus*, however, has been identified as an important marker of episodes of higher downwash in lacustrine sediments (Kołaczek et al. 2013) and might point towards the in-wash of decomposed material from within the Lake Araisi catchment.

Late Iron Age (AD 800–1200)

The Late Iron Age is characterized by fluctuating values of tree taxa. *Alnus* become an important taxon around Lake Araisi at AD 1200. *Picea* decreased at AD 1000. Increasing percentages of ruderal taxa and pollen indicating meadows,

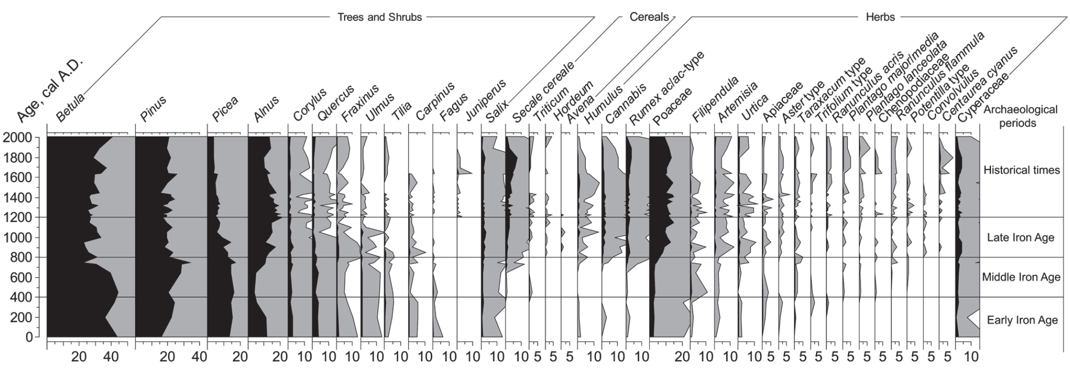


Fig. 4 Diagram of selected pollen (percentages) from Lake Araisi; *grey areas* show multiplication by 10

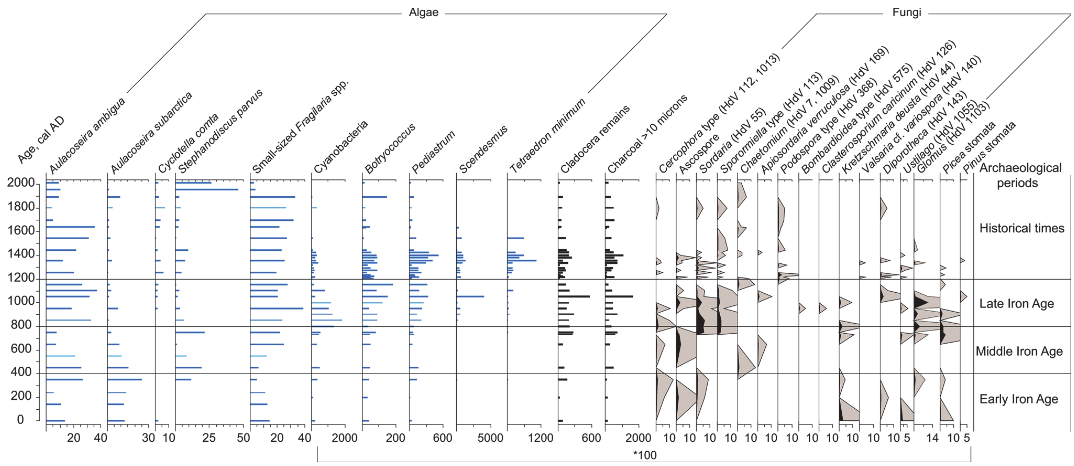


Fig. 5 Diagram of selected diatoms (%) and selected non-pollen palynomorphs (accumulation rate values *100 per cm^{-2} $year^{-1}$) from Lake Araisi; *grey areas* show multiplication by 10

pastures and cultivated land show continued intensive land-use throughout the Late Iron Age (Fig. 4). Among the NAP taxa, Poaceae showed the most abrupt increase up to nearly 15 %. Rapid increase of Cyanobacteria occurred from AD 800 to 1000 and decreased afterwards (Fig. 5). Small-sized *Fragilaria* spp. increased. *Scenedesmus*, Cladocera and charcoal had a distinct peak at AD 1050. Interestingly AR of Cladocera followed the AR pattern of charcoal. Moreover abrupt decrease of *Sordaria* and *Sporormiella*, *Glomus* and other Ascospores was recorded at AD 1050. Also the *Diporotheca* peak recovered at AD 1050. *Diporotheca* may serve here as an indicator of major soil disturbance and extensive soil erosion due to the impact of agricultural activities (Hillbrand et al. 2012).

Historical times (AD 1200–2012)

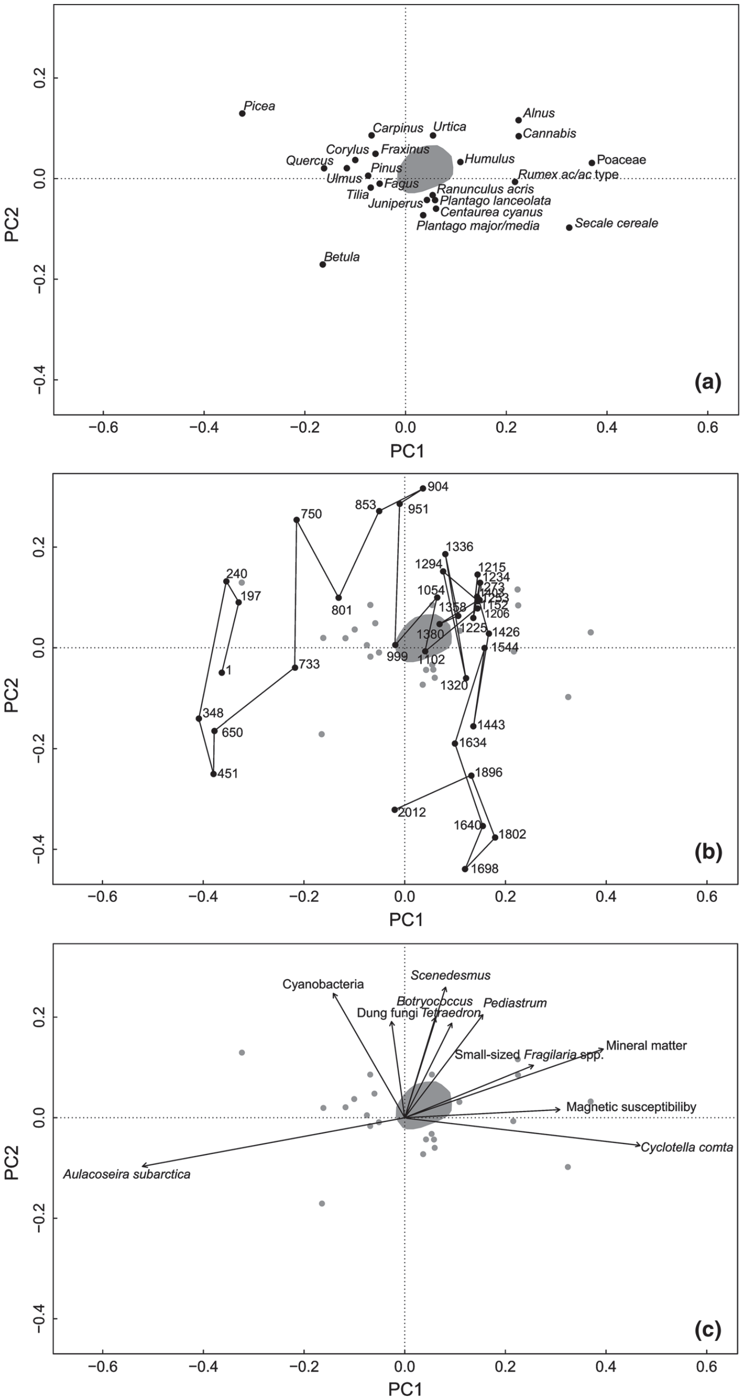
After the highest peak of *Alnus* at AD 1200 its values continuously decreased to 10 % by AD 1800. Other tree taxa like *Picea* stayed at low values, but *Betula* and *Pinus* fluctuated throughout historical times. *Juniperus* appeared as new taxon around AD 1200 and diminished at AD 1800 (Fig. 4). The highest peak of *Secale cereale* occurred at AD 1800–1850 followed by a decrease towards the present day. *Botryococcus*, *Pediastrum*, *Scenedesmus* and *Tetraedron minimum* had elevated ARs from AD 1200 to 1500. Only *Sporormiella* and *Podospora* appeared more frequently throughout historical times (Fig. 5). *Podospora* is one of the coprophilous fungi taxa and might be associated with the presence of herbivores and livestock in general (Cook et al. 2011). *Stephanodiscus parvus* increases after AD 1950.

Statistical analysis

In the PCA analysis, the first two ordination axes were significant in explaining the variance in the pollen data. PCA1 explained 50.4 % of the variance ($p < 0.001$) and PCA2 9.7 % ($p < 0.001$). PCA1 was clearly related to the landscape openness with tree taxa (*Picea*, *Quercus*, *Corylus*, *Betula*) on the left-hand side of the ordination plot and open area indicators (Poaceae, *Secale cereale*, *Rumex acetosa/acetosella*) on the right hand side (Fig. 6a). PCA2 is more difficult to interpret. We suggest it can be related to the nutrient availability with taxa characteristic of fertile soils (*Picea*, *Alnus*, *Carpinus*) being positively associated with PCA2 and taxa related to less fertile soils being negatively associated with PCA2 (*Betula*). The time trajectory of pollen samples shows that the landscape developed from closed forest to semi-open landscape during the first 1,000 years of the study period (Fig. 6b). During the last 1,000 years the landscape was continuously open; only towards the present-day does the importance of the tree taxa increase again.

The “envfit” analysis of associations between the other proxy data and pollen ordination showed that 11 proxy variables were significantly associated with pollen data (Fig. 6c; ESM 2). MM content, MS and the diatom taxa *Cyclotella comta* and *Fragilaria* were positively associated with PCA1 and the diatom species *Aulacoseira subarctica* was negatively associated with PCA1 (Fig. 6c). PCA2 was positively associated with several non-pollen palynomorphs (Cyanobacteria, dung or coprophilous fungi, *Scenedesmus*, *Pediastrum*, *Tetraedron minimum* and *Botryococcus*).

Fig. 6 PCA of **a** pollen, **b** time trajectory of pollen samples and **c** associations between the other proxy data and pollen ordination; *grey elongated area* shows the location of pollen taxa that were indistinguishable and do not have a strong influence on the first two PCA axes



The correlation analysis of the associations between the pollen ordination and element concentrations showed that several elements were significantly positively associated with the first PCA axis: Cobalt (Co) ($r = 0.84$, $p < 0.001$), Iron (Fe) ($r = 0.77$, $p < 0.001$), Potassium (K) ($r = 0.79$, $p < 0.001$), Magnesium (Mg) ($r = 0.8$, $p < 0.001$), Lead (Pb) ($r = 0.79$, $p < 0.001$), Titanium (Ti) ($r = 0.77$, $p < 0.001$), Vanadium (V) ($r = 0.81$, $p < 0.001$) (ESM 3). The only element that was strongly associated with PCA2 was Manganese (Mn) ($r = -0.63$, $p < 0.001$) (ESM 3).

Discussion

Early Iron Age (1–400)

During the Early Iron Age, three tribes (Latgallians, Semigallians and Livs) inhabited eastern and central Latvia. According to archaeological data, the Livs were located to the north-west, Latgallians to the south-east and Semigallians to the south-west of Lake Araisi. Although archaeological evidence for a Semigallian presence in the vicinity of Lake Araisi dates back to the Bronze Age (Apals 2012) our results suggest that the vicinity of Lake Araisi was heavily forested without clear evidence for human activity (Fig. 4; Table 2). Furthermore, the time trajectory of pollen samples (Fig. 6b) and PCA 1 axes (Fig. 7a) indicate that the surrounding landscape was closed (Figs. 6, 7). Besides, phytoplankton such as *Aulacoseira subarctica* point to stable mesoeutrophic conditions.

Middle Iron Age (400–800)

The PCA results (Fig. 6; ESM 2) showed that the landscape was transformed from closed to semi-open during the Middle Iron Age. The first cereal pollen finds of *Secale cereale* and *Triticum* appeared at AD 400 coinciding with a decline in *Alnus* around Lake Araisi from AD 400–700 (Fig. 4). Saarse et al. (2010) showed that the decline in *Alnus* stands during the Iron Age can be associated with human impact linked to the intensification of cultivation in the eastern Baltic area. Reitalu et al. (2013) demonstrated that *Alnus* was positively associated with openness. The appearance of cereal pollen and declining *Alnus* values in the Lake Araisi sediments is accompanied by pollen of ruderal habitats, coprophilous fungi and microcharcoal (Table 2; Figs. 4, 5), strongly indicative of increasing human activities around the lake. This kind of palaeoenvironmental evidence indicates the occurrence of small-scale human populations, engaging in mixed arable and pastoral farming. Cyanobacteria and the planktonic diatom *Stephanodiscus parvus* (Table 2; Fig. 5) suggest that the nutrient status of the lake became more eutrophic, perhaps as a result of increasing anthropogenic erosion of mineral sediment into the lake. Low amounts of anthropogenic pollen indicator taxa before AD 700 suggest that the area around Araisi Lake was probably fairly sparsely populated.

The Middle Iron Age (Migration period) (Graudonis 2001) is characterised by new tribes moving into the area from the south and south-east (Apals 2012). The Semigallians were suppressed by newcomers knows as Latgallians. This invasion of Latgallians would have created a great deal of instability in the landscape that may have required fortified settlements on the island in Lake Araisi also. The first building layer of the Araisi lake-dwelling is dated to ca. AD 780 (Meadows and Zunde 2014) and it was constructed largely of *Picea* logs but with smaller quantities of *Betula* and *Pinus*. The high amount of *Picea* stomata in the lake sediments either suggests spruce forest on the lake shore, the nearby working of spruce timbers along the lake edge, and/or the use of branches in the construction of the dwelling. The island in the lake served as additional protection for the settlers with active use of the land around the lake leaving a distinct signal in the sediment record. Our results demonstrate that there was an abrupt increase in land-use (Figs. 4, 7a), palynological richness (Fig. 7b) and MM (Fig. 7c) demonstrating that there was intensifying land-use slightly earlier than the establishment of the lake-dwelling in AD 750.

Late Iron Age (800–1200)

Increased proportions of herb pollen (Figs. 4, 6a) and the time trajectory of pollen samples (Fig. 6b) suggest transformation of the landscape from semi-open to open at the Late Iron Age. The abundance of the planktonic diatom *Aulacoseira ambigua* (Fig. 5) is in accordance with an increasing openness to winds due to forest clearance around the lake, and stronger and prolonged spring and autumn turnover with more intensive mixing of the water column. Moreover, woodland clearance and increased land-use may have lead to soil erosion in vicinity of Lake Araisi, reflected by the increased MM content and MS (Figs. 6c, 7c, d). In addition, higher erosion indicators are associated with a peak of small-sized epipsammic fragilarioid diatoms that prefer habitation on sand and silt grains. Levels of Ti although not substantially elevated in terms of contamination (ESM 1), do begin to increase in enrichment and may reflect soil erosion into the lake (Lomas-Clarke and Barber 2007) associated with woodland clearance and cereal cultivation surrounding the lake. An abrupt rise in the AR of *Secale cereale* (Fig. 7e) supports the abovementioned clearing of woodland. Moreover, Koff and Punning (2002) suggest that AR values above 1,000 cereal pollen grains cm^{-2} $year^{-1}$ strongly relate to fields

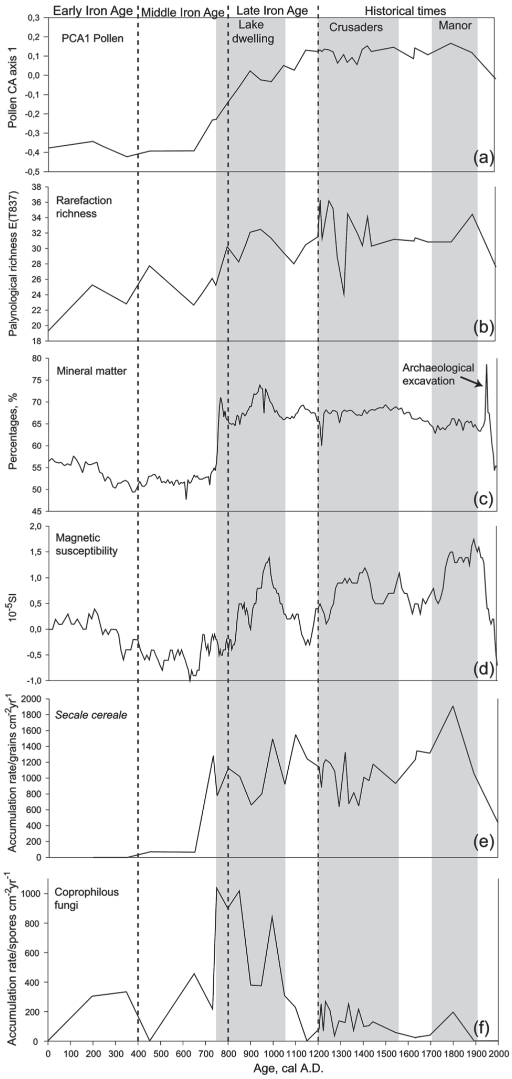


Fig. 7 Different palaeoecological indicators in Lake Araisi: **a** Pollen PCA axis 1, **b** rarefaction estimated palynological richness, **c** mineral matter, **d** magnetic susceptibility, **e** *Secale cereale* **f** coprophilous fungi. Archaeological periodization is marked by *dotted vertical lines* and three main time periods concerning Lake Araisi – lake-dwelling, Crusading and Manor time – are marked by *shaded areas*

within a 2 km radius of a lake. According to our estimates using proxy data from Meltsov et al. (2011) pollen AR of *Secale cereale* in lakes surrounded by forest were below 100 cm^{-2} $year^{-1}$, but lakes with a semi-open to open landscape had more than 1,000 cm¯2 $year^{-1}$. Based on these estimations we can conclude that there were cereal fields within a 2 km radius of Lake Araisi since AD 750. We can suggest that the land around Lake Araisi was covered with pastures, meadows and cereal fields (Table 2; Fig. 4). The success of intensive agriculture in the area during the Late Iron Age was most probably due to the appearance of the iron plough and fertile soils. Finds of Dirham coins from the lake-dwelling suggests the inhabitants were producing enough goods of fibre, fur, wax and victuals for trade and exchange (Apals 2012).

The high abundances of ascospores of coprophilous fungi from AD 780 to 1050 (Fig. 7f), characterised by their highly localised distribution (van Geel 2001) can be attributed to the presence of livestock, particularly herbivores (Cugny et al. 2010; Gauthier et al. 2010; Etienne and Jouffroy-Bapicot 2014), being kept within the lake-dwelling itself during this period. The archaeological evidence also points to the presence of livestock in the settlement, perhaps with a byre similarly to the Alvastra pile-dwelling in Sweden as suggested by Göransson (2002).

The expansion of Cyanobacteria from AD 780 to 1100 suggests further eutrophication of the lake ecosystem, most likely as a result of intensive arable and pastoral activities, including the rearing of animals within the lake-dwelling itself (Table 2; Fig. 5). Similar evidence for increasing eutrophication of a lake resulting from human activity has been reported by van Geel et al. (1994) in Lake Gosciaz, Poland. In addition Cyanobacteria, *Scenedesmus*, *Pediastrum*, *Botryococcus* and dung fungi showed a close relationship to each other (Fig. 6c) which indicated that they all may reflect elevated nutrient input.

Based on our results we argue that the maximum abundance of coprophilous or dung fungi (Fig. 7f) corresponds to settlement of the lake-dwelling from AD 780 to 1050. Archaeological data indicate that the penultimate phase of the lake-dwelling dates to ca. AD 1025 (Punning et al. 1968), but the last layer was burned down during a battle of unknown date (Apals 2012). Although the lake-dwelling endured three fire events it was always restored, except on the last occasion. Microcharcoal evidence (Table 2; Fig. 5) points to a massive fire-event around AD 1050. This event and the sharp decrease of coprophilous fungi may indicate the termination of the lake-dwelling. During the next 50–100 years the trophic state of the lake returned to pre-settlement levels. However intensive agriculture continued in the vicinity of Lake Araisi as shown by the presence and increase of *Secale cereale*, *Triticum*, *Humulus* and *Cannabis* pollen (Fig. 4). It is probable that the lake-dwelling played an important role in the nutrient input into the lake (Fig. 6c), and as people moved away from the lake, the water quality recovered. Makohonienko (2004) suggests that if people move further from the lake edge (or lake itself), the direct impact on the lake reduces to minimal levels whilst the AR of cultural pollen taxa into the lake continues undiminished.

One of the main triggers allowing occupation of the island might have been low lake levels associated with the medieval climate anomaly (MCA). The MCA (ca. AD 750–1350) was characterized by coherent changes in large-scale North Atlantic Oscillation atmospheric circulation patterns. During the MCA dominant westerly winds and higher Baltic sea surface temperature (Kuijpers et al. 2012) resulted in increased annual air temperature of 1–1.5 °C (Korhola and Weckström 2000; Seppä et al. 2009), and reduced summer and annual precipitation (Graham et al. 2010; Kuijpers et al. 2012; Seppä et al. 2009). In addition, decreased surface wetness in bogs and lower lake levels are recorded across northern and eastern Europe (Gałka et al. 2014; Graham et al. 2010; Hammarlund et al. 2003; Lamentowicz et al. 2008; Väliranta et al. 2012). The abandonment of the lake dwelling in the 11th century, if not directly related to its destruction, may have occurred because of increasing lake water levels which made the task of rebuilding and fortifying the site harder and more unfavourable.

Historical times (1200–2012)

Significant economic and political changes in the eastern Baltic occurred with the Christianization and conquest of the Livs and Latgallians by the Livonian Order of the Brothers of the Sword (later incorporated into the Teutonic Order and rebranded as the Livonian Order) (Urban 2003). The landscape of the eastern Baltic was reorganised into administrative units called commanderies, headed by a single castle or convent, run by a commander, and in turn supported by smaller subsidiary castles run by a procurator responsible for administering and managing the resources of a specific part of the commandery. Araisi performed the role of a procurator's castle as part of the Cēsis commandery.

The time trajectory of pollen samples (Fig. 6b) and higher palynological richness (Fig. 7b) possibly point to a slight increase in landscape openness (Fig. 7a) and land-use, but at the same time the changes were not as significant as during the preceding Late Iron Age. The castle at Araisi was not founded until the early 14th century, suggesting that prior to this the form and type of agriculture and land-use continued much as it had during the Late Iron Age. Excavation of the western range of the castle in the 1980s produced a large animal bone assemblage (Apals 2012) suggesting some storage and control of surrounding agricultural resources. However, excavations of the outer bailey and eastern range of the castle in 2012 produced no archaeological evidence, either artefactual or structural, that one would expect from a procurators castle, suggesting the site performed a rather limited role in this respect. The curve for *Secale cereale* pollen suggests at the very least continuity, if not a slight decline, in the intensity of agricultural activity in the immediate landscape during the 13th–15th centuries.

Concentrations of Ni, P, Pb and Zn (ESM 1) are likely to reflect historical contamination relating to nearby settlements. In addition, these elements have been associated with metal-working, craft activities, waste from domestic hearths, organic waste from domestic activities, stabling, manure and cess (Banerjea 2008; Cook et al. 2010; Dockrill et al. 1994; Entwistle et al. 2000; Fernández et al. 2002; Holliday and Gartner 2007; Hutson and Terry 2006; Kemp et al. 1978; Middleton and Price 1996; Pierce et al. 1998; Terry et al. 2004; Wilson et al. 2005, 2008). The increase in Pb from ca. AD 700 (ESM 1) may partly reflect broader atmospheric pollution from Iron Age and medieval metal industries (Renberg et al. 2002). Similar signals have been recorded by Terasmaa et al. (2013) in the Lake Ķūžu sediments located 25 km south of Lake Araisi.

Our results suggests that the crusades in the eastern Baltic (Livonia) differ significantly to the crusades in Prussia (present day north-east Poland) where the conquest by the Teutonic Order was accompanied by significant colonization, evident in the form of both urban foundations and numerous rural settlements, all secured by heavily fortified castles (Pluskowski 2012). Palaeoenvironmental data from Prussia record significant agricultural intensification associated with the crusades, although this occurs as part of a process of increasing land-use beginning with Slavic colonisation in the 8th century and Polish expansion from the 10th century (Brown and Pluskowski 2014; Pluskowski and Brown 2012). Colonization in the eastern Baltic was limited largely to the major urban centres, such as Riga, with limited colonization of the rural hinterlands, with native populations continuing to follow indigenous patterns of land-use (e.g. Mugurēvičs 2008).

Slight increases in cereal cultivation during the Post-medieval period suggest that the human impact on the environment compared to the previous medieval period was fairly limited in vicinity of Araisi. Intensification of land-use, crop cultivation and possibly more open landscape (Figs. 6b, 7a) reached its peak during the Manor time (AD 1750–1900) as indicated by the highest values of magnetic susceptibility, *Secale cereale* and *Centaurea cyanus*. Change in pollen PCA1 and palynological richness (Fig. 7a, b) indicates a definite change in the vegetation composition after AD 1800 with agricultural landscape reaching its highest levels during the last 2,000 years (Figs. 6b, 7a). Our results correspond well to the study of Lake Rõuge Tõugjärv in southern Estonia (Veski et al. 2005) that shows a pattern of extensive farming, where the growth in population was compensated by the increasingly large areas of land placed under cultivation. This pattern prevailed until the AD 1850s, when cereal cultivation shifted from extensive to intensive farming with more effective use of the existing land.

In addition to the environmental impact of the Late Iron Age, medieval and Post-medieval communities, it is also possible to distinguished more recent impact on the lake, namely the large-scale archaeological excavations of the lake dwelling from AD 1965 to 1979. During the excavations, the water level of Lake Araisi was lowered by 1 m (Apals 2012), the outflow was deepened and embankments were constructed around the excavation area, with excess water pumped out. This caused large-scale sediment disturbance in the western end of the lake, resulting in additional MM inputs at the sampling site (Fig. 7c). High abundance of the eutrophication indicator *Stephanodiscus parvus*, and the appearance of the hypereutrophic diatoms *S. hantzschii* and *Cyclostephanos invisitatus* show in-lake nutrient enrichment and distinct deterioration of the water quality.

Conclusions

The present study is the first detailed multi-proxy palaeoenvironmental investigation associated with Late Iron Age lake dwelling sites in the Baltic region. Our study reveals that the most significant changes in vegetation and environment during the last 2,000 years occurred during the establishment phase of the lake-dwelling around AD 780. Before this the vicinity of Lake Araisi was covered by forests and small-scale human-activity with the first appearance of cereal pollen (*Triticum* and *Secale cereale*) around AD 400. The highest AR of coprophilous fungi coincide with the occupation of the lake-dwelling from AD 780 to 1050 indicating that parts of the settlement functioned as byres for livestock. The three centuries between the abandonment of the lake dwelling and construction of the castle on the lake shore are characterised by continued settlement and agricultural activity within the surrounding landscape. Archaeological excavations at the castle and palaeoenvironmental results show that the importance of the castle has been overestimated; it had a rather limited role and impact on land-use during the medieval period. The impact of the crusades appears to be concentrated on the key urban centres, with little ecological impact on rural hinterlands and limited impact on the way of living of the indigenous populations. Thus the form and type of agriculture and land-use may well have continued much as it had done during the preceding Late Iron Age. The impact of recent archaeological excavations of the lake-dwelling is also apparent in the lake record: it involved a lowering of lake levels and is visible as a clear peak in MM content. It suggests that lake sediments are sensitive for reflecting short-term human impact and serves to emphasise the fragility of lake ecosystems to sudden environmental change.

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Quantitative summer and winter temperature reconstructions from pollen and chironomid data between 15 and 8 ka BP in the Baltic–Belarus area

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A B S T R A C T

New pollen based reconstructions of summer (May-to-August) and winter (December-to-February) temperatures between 15 and 8 ka BP along a S–N transect in the Baltic–Belarus (BB) area display trends in temporal and spatial changes in climate variability. These results are completed by two chironomid-based July mean temperature reconstructions. The magnitude of change compared with modern temperatures was more prominent in the northern part of BB area. The 4 C° winter and 2 C° summer warming at the start of GI-1 was delayed in the BB area and Lateglacial maximum temperatures were reached at ca 13.6 ka BP, being 4 C° colder than the modern mean. The Younger Dryas cooling in the area was 5 C° colder than present, as inferred by all proxies. In addition, our analyses show an early Holocene divergence in winter temperature trends with modern values reaching 1 ka earlier (10 ka BP) in southern BB compared to the northern part of the region (9 ka BP).

1. Introduction

Reconstructing past abrupt and extreme climate change beyond 8 ka using continental palaeoclimatic records is a challenge, but the task is essential to better understand the mechanisms of rapid climate change in terrestrial environments. Quantitative reconstructions based on fossil pollen and chironomids are widely used and useful for long-term climate variability estimations. The chironomid-based reconstructions, for example, indicate LG temperature patterns and gradients which agree with the simulations based on palaeoclimate modelling (Heiri et al., 2014). However, the Lateglacial (LG) and early Holocene rapidly changing natural and climatic environments with potential non-analogue climatic conditions may limit the reliability of the pollen-based reconstructions, as available calibration sets are based on modern pollen assemblages that in many regions may have poor analogues for vegetation during the late Pleistocene and early Holocene. Therefore, producing pollen-based climate reconstructions for these possible non-analogue environments and their climates can be a difficult task. A possible way to circumvent this problem is to use larger calibration sets to better cover possible combinations of climate parameters that may have existed during the Lateglacial environment. Such larger calibration sets can therefore cover biomes such as taiga, steppe, forest–tundra and tundra, but this will increase the geographical range of the surface samples and reduces the taxonomic accuracy of the calibration data as key vegetation components may not be adequately present or may be spatially restricted in different regions encompassed in the investigated area (Salonen et al., 2012a, b; 2014).

The Lateglacial and early Holocene period (15–8 ka BP) in the Baltic–Belarus (BB) area was characterized by sudden shifts in climate due to various climate forcings affecting the climate of the northern hemisphere and North Atlantic, including the proximity of receding ice sheets. Climate variations in BB during the LG were eminent as the southern part of the region was ice free during the Last Glacial Maximum (LGM) over 19 ka BP, whereas northern

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Estonia became ice free no sooner than 13 ka BP (Saarse et al., 2012). For decades, it has been known that the warming at the beginning of the Bølling-Allerød interstadial (equivalent to GI-1; Björck et al., 1998) at ~14.6 ka BP and the Holocene at ~11.7 ka BP, together with the Younger Dryas (YD) 1000 year cooling episode 12.7–11.7 ka BP and the 8.2 ka BP event were prominent climatic events in the area, but accurate, quantitative reconstruction of past temperatures for the BB area have been missing. Pollen-based climate reconstructions cover the last 9 ka BP in Northern Europe (Seppä et al., 2009) and the Baltic area (Seppä and Poska, 2004; Heikkila and Seppä, 2010) but do not encompass older intervals. Salonen et al. (2012a, b) provided a new 113 sample calibration set that covers a May-to-August temperature range from 17.3 °C to 5.9 °C across forest-to-tundra ecotones from Scandinavia to NW Russia. This new dataset provides new opportunities for reconstructing LG temperatures based on pollen records from the BB area (Salonen et al., 2014).

The aim of the INTIMATE project, to compile and correlate high-quality climatic and vegetation records for the past 60–8 ka with Greenland ice core data, prompted us to provide quantitative climate reconstructions for the LG period from the Baltic–Belarus area. First, we use pollen data to reconstruct summer and winter temperatures between 15 and 8 ka BP in the BB area over a S–N transect from southern Belarus to northern Estonia, including data from 8 sites. The area extends from beyond the limits to within the range of the last glaciation of the Scandinavian Ice Sheet (SIS). We estimate the temporal and spatial magnitude of the climate variability. In a second step, we compare our reconstructions with LG

Fig. 1. Baltic–Belarus study area with investigated sites as black dots (Table 1). Ice marginal positions of the deglaciation of the last Scandinavian ice sheet are shown as lines (Kalm, 2012).

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temperature records derived from other proxies such as chironomid based July mean air temperature reconstructions from two of the same sites as the pollen data.

2. Study area

Our study area (Fig. 1) covers the Baltic–Belarus area (~200 000 km^2) east of the Baltic Sea with Estonia (60° N) in the north and Belarus (51° N) in the south. The topography has largely been shaped by the Scandinavian Ice Sheet during the last glaciation and its retreat, as the region is situated in the southeastern part of the area which was covered by the SIS (Kalm, 2012). The S–N transect of eight investigated and previously published fossil pollen records span the distance of nearly 900 km. The southern end of the investigated area (lakes Sergeevskoe (also Sergeyevskoye), Dvorischchanskoye (also Dvorishchanskoje)) in Belarus remained ice-free during the LGM approximately 20 ka BP, as the maximum extent of the SIS ran approximately along the Lithuanian-Belarus border and covered northern Belarus. Lake Mezhuzhol (also Mezhyzhol) in Belarus lies at the LGM limit. The mid-Baltic sites Kurjanovas and Lielais Svetinu in Latvia and Petrašiunai in Lithuania were deglaciated 14.5 ka BP and the northernmost sites lakes Nakri and Udriku in Estonia 14 ka BP. The SE part of the area might have been a refugium for several tree taxa (e.g. spruce) during the LGM (Giesecke and Bennett, 2004; Tollefsrud et al., 2008). The LG vegetation of the area was rapidly changing, ranging from steppe (outside the LGM), tundra, forest-tundra to forest, depending on climate as well as the proximity of the ice sheet. An important palaeogeographical feature of the northern part of the deglaciated region was the formation of ice-dammed lakes and major melt water spillways that shaped the LG landscape (Amon et al., 2014). The modern climate range of the BB area is a transition zone from western oceanic and eastern continental climate with summer (May–June–July–August, MJJA) temperatures (1961–1990) 15 °C in Estonia and 16 °C in Belarus and winter (December–January–February DJF), temperatures −4.5 °C and −5 °C respectively.

3. Material and methods

Pollen-based quantitative climate reconstructions were performed from eight fossil pollen records (Table 1), which cover the LG and early Holocene from 15 to 8 ka BP, spanning nearly 900 km and covering the BB region. Approximately 500 pollen grains were counted from each sample. Tree pollen types that were considered exotic to the LG environment, such as thermophilous taxa *Alnus*, *Corylus*, *Tilia*, *Quercus*, *Ulmus*, *Fraxinus*, and *Carpinus*, presumably inwashed from older deposits and redeposited in the late-glacial lake sediments, were not included in the reconstructions (Veski et al., 2012). The cores were dated with AMS radiocarbon dating, and the age-depth models used were the same as in the original papers.

The pollen-based reconstructions of summer (MJJA) and winter (DJF) mean temperature were reconstructed using two pollen-climate calibration sets, FSELRK and FSER (Salonen et al., 2012b). All modern pollen samples in these sets represent surficial lake sediment (10–20 mm) collected from small and medium-sized lakes (Seppä et al., 2004; Salonen et al., 2012b). The transfer functions used for quantitative reconstructions are based on weighted averaging partial least squares (WA-PLS) regression and calibration technique (ter Braak and Juggins, 1993), a generally robust reconstruction method that has the important advantage that it performs relatively well under non-analogue conditions, such as may have occurred during the late-glacial (Juggins and Birks, 2012). The modern values of MJJA and DJF were obtained from the WorldClim dataset (Hijmans et al., 2005). The statistics of the two sets are presented in Table 2. Briefly, dataset FSER includes 197 modern pollen samples from Finland, Sweden, Estonia and western Russia and dataset FSELRK 250 modern pollen samples from Finland, Sweden, Estonia, Lithuania, western Russia, and Komi in northern Russia. FSER is a selection of the FSELRK data set. The reason for using two sets for temperature reconstructions is the because absolute values generated by the reconstruction model may differ according to the temperature gradient and continentality of the calibration data that forms the basis for an inference model. Salonen et al. (2013) tested this by creating alternate calibration data sets via stratified random sampling and demonstrated that palaeoclimatic reconstructions using methods based on taxon-response models can be highly sensitive to the calibration data set used.

Table 2
Characteristics of the modern pollen-calibration sets.

	FSELRK (summer)	FSELRK (winter)	FSER (summer)
Number of sites	250	250	197
Temperature gradient	11.9 °C	24.7 °C	9.2 °C
Temperature range	3.7–15.6 °C	−0.9 to 25.6 °C	6.2–15.4 °C
Number of taxa	114	114	109
r^2	0.83	0.86	0.84
RMSEP	0.98 °C	1.88 °C	0.81 °C

Climate reconstructions were carried out from fossil pollen data from previously published eight sites in the BB region (Table 1). All terrestrial pollen and spore types from these sites were used in the reconstructions. Summer (MJJA) and winter (DJF) temperatures were reconstructed with the FSELRK calibration set. For comparison, summer temperature was reconstructed with the FSER set to be able to explore the possible influence of the selection of the calibration set on the reconstructed LG summer temperature values in our data.

We compare pollen-based reconstructions with the two individual chironomid-based temperature records which in Heiri et al. (2014) are used to present a regional temperature reconstruction

Table 1
Characteristics of the fossil pollen records used for the climate reconstructions.

No	Site code	Site name	Altitude	Longitude	Latitude	Country	No of samples	No of dates	Reference
1	UDR_{EST}	Udriku	95	59°22′16.62″N	25°55′50.44″E	Estonia	19	6	Amon and Saarse 2010; Amon et al., 2014
2	NAK_{EST}	Nakri	48	57°53′42.03″N	26°16′23.04″E	Estonia	89	12	Amon et al., 2012
3	$LSVET_{LAT}$	Lielais Svetinu	96	56°45′32.69″N	27° 8′56.84″E	Latvia	84	14	Veski et al., 2012; Stivrins et al., 2014
4	$KURJ_{LAT}$	Kurjanovas	111	56°31′52.55″N	27°59′14.34″E	Latvia	54	6	Heikkilä et al., 2009; Heikkila and Seppä, 2010
5	$PETR_{LIT}$	Petrašiunai	107	55°50′49.62″N	25°42′8.05″E	Lithuania	76	6	Stančikaitė et al., 2009
6	$MEZH_{BEL}$	Mezhuzhol	171	55° 0′7.27″N	28° 4′25.35″E	Belarus	52	3	Zernitskaya and Mikhailov 2009; Novik et al., 2010
7	$SERG_{BEL}$	Sergeevskoe	163	53°30′33.04″N	27°45′43.63″E	Belarus	71	4	Makhnach et al., 2009
8	DVO_{BEL}	Dvorischchanskoye	158	51°42′14.13″N	23°59′27.67″E	Belarus	47	4	Zernitskaya and Kalicki 2008

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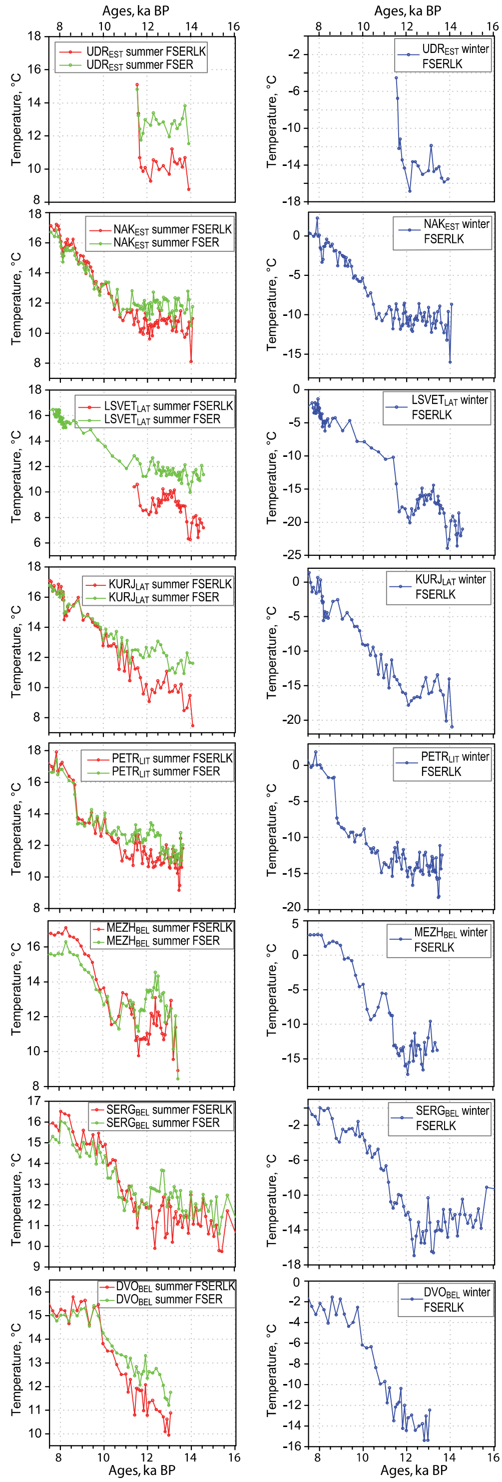

Fig. 2. Reconstructed climate parameters summer and winter temperature based on pollen assemblages for the individual sites according to two climate inference models FSELRK and FSER. Sites are arranged from south to north.

for the Baltic region. The approach for reconstructing past July air temperature based on chironomid assemblages is described in more detail in this study. In brief, chironomid-based palaeotemperatures were reconstructed using an inference model (Heiri et al., 2011) based on subfossil chironomid assemblages in surface sediments from 274 lakes in Norway and the Swiss Alps and associated modern July air temperature data. The 2-component WA-PLS inference model is characterized by a Root Mean Square Error of Prediction (RMSEP) of 1.40 °C and a coefficient of determination (r^2) of 0.87 if evaluated within the calibration data using bootstrapping (9999 bootstrap cycles). Sediment samples for down-core reconstruction, which formed the basis for these temperature records, were prepared for analysis using standard methods (Brooks et al., 2007).

To compare the performance of the two summer temperature reconstructions, we assessed whether the estimated mean temperatures differed significantly between the reconstructions. For this, we used an Analysis of Variance (ANOVA) with model identity as explanatory variable and the reconstructed temperature as response variable. The analysis was performed separately for LG and early Holocene. In addition, we calculated correlations (Pearson's product moment correlations) between the pollen-based summer temperature reconstructions and existing chironomid-based July mean temperature reconstructions (Heiri et al., 2014), separately for each site and both models. The Chironomid data was only available for the LG period.

To summarize the general temperature variation in the area, we used Local weighted regression (LOESS) smoothing with the span (α) of 0.1. We calculated the LOESS curves separately for the northern and southern BB sites.

4. Results

4.1. Lateglacial

The individual pollen-based summer and winter temperatures of the FSELRK and FSER models are presented on Fig. 2. Although the southernmost sites were located outside of the LGM limit and the northernmost sites were deglaciated 14 ka BP, the start of sedimentation occurred approximately at the same time, around 14–13 ka BP, at all sites. The exception is site SERG$_{BEL}$ which displays a record back to 16 ka BP. For summer temperature, the FSELRK model estimates generally colder temperatures than the FSER model in the LG and warmer temperatures during the Holocene. This feature can be explained with the relative importance of Komi (colder) reference sites in the calibration dataset.

The mean summer temperature in Belarus in the LG was around 11 °C (DVO$_{BEL}$ to MEZH$_{BEL}$) according to the FSERK model and 12.1 °C–12.6 °C according to the FSER model (Table 3). The highest pollen inferred summer temperatures in the LG in Belarus were ~12 °C (FSELRK). Higher values, around 13–14 °C, were reconstructed by the FSER model. Lowest summer temperatures below 10 °C were associated with the basal parts of the cores and with the YD (GS-1) period. The LG amplitude of change of the summer temperatures was around 3 C° in Belarus. The two southernmost sites do not display clear variability in the GI-1 and GS-1 warming and cooling. The mid-Baltic sites MEZH$_{BEL}$, PETR$_{LIT}$, KURJ$_{LAT}$ and LSVET$_{LAT}$ show distinct summer temperature change and variability, with cool summers in early GI-1, warming around 13 ka BP and evident GS-1 cooling centred around 12 ka BP. The pollen inferred summer temperature of the mid-Baltic sites $PETR_{LIT}$, $KURJ_{LAT}$ and $LSVET_{LAT}$ in Lithuania and Latvia within the LGM limit is clearly cooler than the southern sites, from 11.1 °C (FSELRK) and 11.9 °C (FSER) in $PETR_{LIT}$ to 8.6 °C (FSELRK) and 11.4 °C (FSER) in $LSVET_{LAT}$. There is a visible trend in reconstructed summer temperatures from south to north (DVO_{BEL} – $LSVET_{LAT}$) along the deglaciation path. The range of mean LG FSELRK MJJA temperature is ~2.5 °C, the proximal sites having colder summers according to the reconstruction. The same holds true for the FSER model, but with lesser temperature range encompassed by the reconstructions. The northernmost sites UDR_{EST} and NAK_{EST} are exceptional with reconstructed summer temperatures higher than in the south. This is explained by the location of the LG northern range limit of trees around Nakri (Amon et al., 2014). Hence, there are no tree macrofossil finds north of Lake Nakri in Estonia, and the pollen accumulation rates are low, which explains the distorted nature of the pollen data with overwhelmingly high proportion of long distance and re-sedimented pollen grains in the pollen spectra.

13 ka BP. The mid-Baltic sites $PETR_{LIT}$, $KURJ_{LAT}$ and $LSVET_{LAT}$ have generally colder LG average winter temperatures, −14 to −18 °C, the GS-1 cold winters are −20 °C, and the early LG winters before 13.5 ka BP are reconstructed as even colder.

The YD MJJA temperatures are around 11 °C (FSELRK) and 12 °C (FSER) in the south and around 9–10 °C in Latvia (LSVET and KURJ). The YD winter temperature ranges from −13 to −17.5 °C.

The Bølling–Allerød (GS-1) MJJA temperatures are around 10 °C (FSELRK) and 11 °C (FSER) all over the region. The GS-1 winter temperature ranges from −12.6 to −16.8 °C.

4.2. Early Holocene

Early Holocene (11.7–8 ka BP) temperature change (both in the FSELRK and FSER models) is illustrated by a steady rise in summer and winter temperatures after the YD. The early Holocene MJJA temperature is around 14 °C throughout the region, and the winter temperature varies more (Table 3). The amplitude of temperature change from 11.7 to 8 ka BP in summer is 3–4 C°, whereas the winter temperature amplitude is over 10 C° in the mid-Baltic area and somewhat less in the southernmost and in the northernmost sites. The cooling around 8.2 ka BP is clearly observable in the winter data of adequate resolution (NAK_{EST} and $KURJ_{LAT}$), the amplitude is generally 2 C°.

Table 3
Temperature means for the Lateglacial and early Holocene.

Site code	LG MJJA FSELRK mean, °C	LG MJJA FSER mean, °C	LG winter mean, °C	YD (GS-1) MJJA FSELRK mean, °C	YD (GS-1) MJJA FSER mean, °C	YD (GS-1) DJF mean, °C	GI-1 MJJA FSELRK mean, °C	GI-1 MJJA FSER mean, °C	GI-1 DJF mean, °C	HOL MJJA mean, °C	HOL winter mean, °C
UDR_{EST}	10.2	12.6	−14.2	10.1	12.7	−13.8	10.4	12.8	−14.4	NA	NA
NAK_{EST}	10.5	11.8	−10.7	10.6	11.8	−10.5	10.8	11.7	−10.4	13.7	−5.0
$LSVET_{LAT}$	8.6	11.4	−18.3	9.1	11.8	−17.5	9.2	11.4	−16.8	14.4	−6.4
$KURJ_{LAT}$	9.7	12.0	−16.2	10.0	12.5	−16.4	10.1	11.6	−15.0	14.1	−7.2
$PETR_{LIT}$	11.1	11.9	−14.3	11.1	11.4	−14.2	10.9	11.4	−14.6	13.3	−9.6
$MEZH_{BEL}$	11.2	12.6	−13.9	11.2	13.1	−14.4	11.0	11.3	−12.7	13.7	−4.7
$SERG_{BEL}$	11.3	12.1	−13.0	11.6	12.5	−13.0	10.2	11.2	−12.6	14.1	−4.5
DVO_{BEL}	11.1	12.3	−13.3	11.3	12.5	−13.0	10.5	11.5	−13.6	14.0	−6.2

The pollen-based LG summer and winter temperature reconstructions have their shortcomings due to the limited control on the pollen source area for the individual records with sites inside the forest limit with "normal pollen deposition" and sites in treeless vegetation with overrepresentation of exotic pollen. Therefore, July mean temperatures (T_{Jul}) reconstructed from fossil chironomid sequences from NAK_{EST} and $KURJ_{LAT}$ (Heiri et al., 2014) represent an alternative method for climate reconstructions, and make it possible to compare the results based on these two independent approaches (Fig. 3). Such a comparison shows that the amplitude of temperature change in the records is comparable. The chironomid inferred T_{Jul} in mid-Baltic area ranges from ~11 °C around 14 ka BP to 14 °C during the GI-1 optimum 13.6–12.8 ka BP (Fig 3). The YD cooling lowered the T_{Jul} to ~11 °C.

The reconstructed LG winter temperature displays a similar trend, with warmer mean winter temperatures (−13 °C) in the southern part of Belarus compared to mean winter temperature of −18.3 °C around $LSVET_{LAT}$ and with much warmer winters in UDR_{EST} and NAK_{EST}. The winter temperature values of these latter sites may be unrealistically high due to the problem of low tree pollen productivity. A certain share of "alien" tree pollen grains might be present at all the investigated sites, and there could be a trend where northern sites are more contaminated i.e. enriched with long distance and re-sedimented pollen grains than the southern ones. The mean winter temperature in Belarus in the LG ranges between −13 °C in $SERG_{BEL}$ to −13.9 °C in $MEZH_{BEL}$ according to FSER (Table 3). Lowest winter temperatures between −17 and −15 °C were associated with the YD (GS-1) period. Warmer pollen inferred winter temperatures of −10 to −11 °C in the LG in Belarus were observed during GS-1 around

The pollen inferred summer and winter temperatures were correlated with July air palaeotemperatures reconstructed from fossil chironomid sequences from Nakri and Kurjanovas lakes in Estonia and Latvia (Heiri et al., 2014) as independent climate variables. The correlation is significant with the FSERLK model MJJA temperatures, whereas no correlations are apparent with the MJJA temperatures reconstructed with the FSERLK data (Table 4).

Table 4
Correlations of pollen inferred temperatures from different sites with chironomid-based July mean temperature estimations from Kurjanovas ($KURJ_{LAT}$) site.

Site	FSERLK (summer)	FSER (summer)	FSERLK (winter)
UDR_{EST}	0.3 n.s	−0.26 n.s	0.02 n.s
NAK_{EST}	0.48*	0.02 n.s	0.23 n.s
$LSVET_{LAT}$	0.61**	−0.29 n.s	0.63**
$KURJ_{LAT}$	0.61**	0.2 n.s	0.65**
$PETR_{LIT}$	0.13 n.s	−0.19 n.s	0.1 n.s
$MEZH_{BEL}$	0.61*	−0.21 n.s	0.68**
$SERG_{BEL}$	0.68***	0.31 n.s	0.56**
DVO_{BEL}	0.33 n.s	0.09 n.s	0.59*

The comparison of the two transfer functions (FSELRK and FSER) with ANOVA showed that the mean summer temperatures estimated by FSELRK were significantly ($p < 0.05$) lower than the summer temperatures estimated by FSER in all sites in LG.

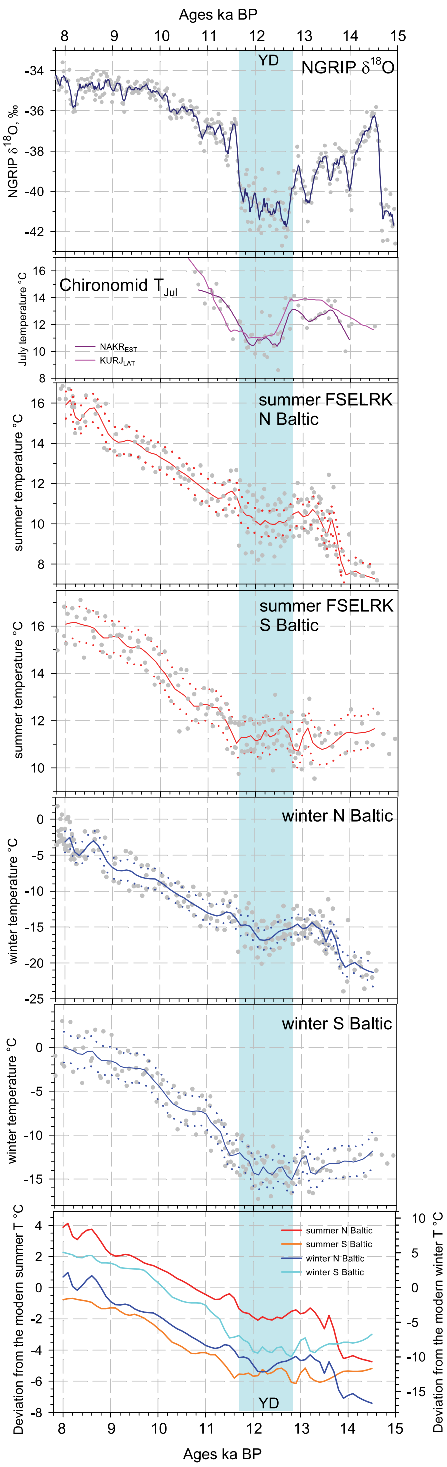

Fig. 3. Average pollen and chironomid inferred temperature variation in the Baltic–Belarus area compared with NGRIP $\delta^{18}O$ variation (Rasmussen et al., 2006). Grey dots indicate original data points, lines indicate LOESS smoothers fitted to the temperature data (span (α) of 0.1) separately for the northern (UDR_{EST}, NAK_{EST}, $LSVET_{LAT}$, $KURJ_{LAT}$) and southern ($PETR_{LIT}$, $MEZH_{BEL}$, $SERG_{BEL}$, DVO_{BEL}) BB sites. Light blue shading marks YD. Chironomid-inferred temperature data are from the Heiri et al. (2014) dataset. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

However, in the early Holocene, there was no significant difference ($p > 0.05$) between the models in any of the sites. Summer temperatures estimated by FSELRK were significantly ($p < 0.05$) positively correlated with chironomid-based temperatures in five out of seven sites, but none of the FSER-estimated summer temperatures was significantly correlated with chironomid-based July temperatures (Table 4).

5. Discussion

A number of syntheses of pollen based quantitative climate reconstructions exist from the northern Baltic area (Velichko et al., 1997; Seppä and Poska, 2004; Seppä et al., 2004; Seppä et al. 2009, 2009; Heikkilä and; Feurdean et al., 2014) covering most of the Holocene, and in Wohlfarth et al. (2004) including the LG. No pollen-based quantitative temperature reconstructions have been earlier carried out in the southern Baltic–Belarus area, but qualitative LG climate reconstructions have been attempted based on stable isotopes (Makhnach and Zernitskaja, 2010). LG vegetation changes are rather well-known in the area (see references in Table 1) and summer and winter temperatures reconstructed based on the well-dated pollen sequences are discussed in this paper (Figs. 2 and 3). Although the southern BB sites are beyond the limits of the LGM ice sheet margin, the sediment cores reach only to 14 ka BP, with the exception of $SERG_{BEL}$ and $LSVET_{LAT}$ where the start of GI-1 warming at 14.6 ka BP is visible. The GI-1e warming is seen as a ~4 C° winter temperature rise and a 2 C° rise in summer temperature in $LSVET_{LAT}$. As a comparison, the chironomid-based July temperature values (Heiri et al., 2014) also differ from the modern mean July temperature by 4 C°, and July temperature during GI-1e ranged between 12 and 12.9 °C in Poland (Plociennik et al., 2011). The early GI-1 was followed by the sudden and short-lasting GI-1d cold spell (NAK_{EST}, $LSVET_{LAT}$ and $KURJ_{LAT}$). Generally, the peak of GI-1 warming was delayed in the BB area compared with the warming as observed in the Greenland ice core data and during the LG maximum MJJA temperatures were reached only at 13.6 ka BP and were lower than the modern mean by 4 C°. Our results showed that the winter temperature was 8 C° colder than today in the south and over 10 °C colder than today in the northern BB area. Velichko et al. (1997) estimated the Allerød (GI-1a) July temperatures in Karelia to be 4 C° and January temperatures to be 10 C° below the present level. The corresponding values for Belarus were around 1–2 C° colder (Bogdel et al., 1983; Velichko et al., 1997): the temperature change was much less evident than in the north. Our reconstructions for Belarus show that the magnitude of change compared with modern temperatures was larger than in northern BB. Another feature is that the southern BB (52° N) winter temperatures reached the modern values ca. 1 ky earlier than the northern part (59° N), whereas an opposite trend is illustrated by the summer temperatures, indicating winter warming and cooler summers in the south.

The YD cooling is evident in all sites as a drop in temperatures. The summer temperatures during the YD in the pollen-based reconstructions deviated from the modern mean by −5 C° in both the north and in the south of the BB region, and the winter temperature deviation showed latitudinal differences, with −12.5 C° change in the north of the BB region and −11 C° in the south of the BB region, as an effect of the proximity of the Scandinavian ice sheet. The chironomid-based July temperature values show a stronger drop of 2–3 C° and were more than 5 C° lower than present. In general, the eastern European chironomid based temperatures reveal warmer summers compared to the west (Brooks and Langdon, 2014; Heiri et al., 2014).

These reconstructions can be compared with the July and January mean temperature values simulated with the ECHAM4 model for the BB region in Renssen and Isarin (2001). For the YD, both pollen and chironomid-based summer temperature reconstructions are roughly in line with the models, but the ECHAM4 model suggest markedly lower winter temperatures than the pollen-based data. Hence the simulated gradient of January mean temperature during the YD is from −27 °C to −20 °C from Estonia to Belarus, while the reconstructed winter temperature is −16 °C in northern parts of BB and −14 °C in the southern part of the BB area.

There is a geographical divergence in the early Holocene palaeotemperature rise in the BB region. The summer temperature reconstructions indicate that modern values were reached approximately 9 ka BP both in northern and southern BB. However, southern BB winter temperatures reached modern values earlier, about 10 ka BP, compared to the northern part of BB where modern values were reached 9 ka BP, consistent with temperature reconstructions from more southern areas in eastern central Europe (Feurdean et al., 2008). The 8.2 ka BP cold event is clearly evident in northern BB area as a 2–3 C° winter temperature drop (the change in MJJA temperature is about 1 C°) but is not recorded in southern BB. This supports the idea that the 2 C° annual mean temperature change (Veski et al., 2004) is mainly attributed to changes in winter temperature and agrees with the geographical pattern of the temperature 8.2 ka BP temperature change in Scandinavia (Seppä et al., 2007) and in more continental areas (southern BB) where the cold signal is less clear (Wiersma et al., 2011).

6. Conclusions

New pollen based reconstructions of summer and winter temperatures between 15 and 8 ka in the Baltic–Belarus area stretching from southern Belarus to northern Estonia display clear trends in temporal and spatial change in the Lateglacial climate variability. The magnitude of change compared with modern temperatures was larger in northern BB than in the south. The 4 C° winter and 2 C° summer GI-1 warming was delayed in the BB area and LG maximum temperatures were reached at 13.6 ka BP and were about 4 C° lower than the modern values. Different reconstructions show consistently that the YD summer temperature in the area was about 5 C° lower than the present. We observe an early Holocene divergence in the winter temperature trend with modern values in southern BB reached 1 ka earlier (10 ka BP) compared to the northern region (9 ka BP).

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Phytoplankton response to the environmental and climatic variability in a temperate lake over the last 14,500 years

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Abstract

Phytoplankton is a primary producer of biomass in the lakes and any shift in their diversity, production has an impact on other aquatic life forms and the food-web structure of the aquatic ecosystem. Here we use environmental factors to explore the drivers of variability of phytoplankton composition over the last 14,500 years in eastern Baltic. Using record of pollen and non-pollen palynomorphs, temperature reconstructions and lithological information as environmental explanatory data we statistically test long-term phytoplankton composition changes in temperate lake. Our results showed that mean annual temperature and landscape openness were significant explanatory variables during both Late-Glacial and Holocene. According to Redundancy analysis and Generalized Least Squares models water tolerance – indicating moist and unstable soil conditions in the surroundings of the lake – was positively associated with *Tetraedron minimum*, *Scenedesmus* and *Pediastrum*. In addition, early Holocene (11,650 – 8,000 cal yr BP) was characterized by highest phytoplankton diversity suggesting environmental heterogeneity. Rarefaction analysis showed that higher phytoplankton diversity in the Late-Glacial was during the warm Bølling-Allerød interstadial, but in the Holocene during the cooler early and late Holocene. Cyanobacteria domination was initiated since 8,000 cal yr BP when mean summer temperature was over 2 °C higher than today and lake was surrounded by dense temperate forest vegetation. Our results illustrate that if aquatic systems experience increases in temperature that favour cyanobacteria over other phytoplankton. However raise in nutrient loading was more important for the biomass enhance of cyanobacteria than the increase in temperature alone. In addition, phytoplankton composition and microfossils permit to specify length of transition from Holocene Thermal Maximum to late Holocene what started with eutrophication-hypereutrophication of the lake at 4,000 cal yr BP and terminate with returning to lower nutrient status at 2,000 cal yr BP.

Keywords: Phytoplankton, Cyanobacteria, Non-pollen palynomorphs, Late-Glacial, Holocene, Temperature

Introduction

Climate-driven physical changes exert strong impacts on aquatic ecosystems (Winder and Sommer 2012). Relatively small and closed lakes in temperate and boreal zones are often used in palaeoecological reconstructions because they are sensitive to climate changes and integrate information about changes in the lake basin and its catchment (Seppä et al. 2009). Diatoms have commonly been analysed in paleolimnological studies but only a few studies have focused on the composition changes of other phytoplankton, such as green algae and cyanobacteria (Jankovská and Komárek 2000; Veski 1994; Weckström et al. 2010). Therefore there is a lack in these studies and in this paper we address issues concerning long-term phytoplankton composition dynamics excluding diatoms.

Many freshwater phytoplankton species have not only worldwide distributions but also specific growth conditions (Demske et al. 2013). In acidic, dystrophic water bodies, the phytoplankton consists mostly of green algae, whereas the importance of cyanobacteria increases in neutral and alkaline lakes (Padisák 2004). In addition, their abundance and composition is determined mainly by light conditions, temperature and nutrient concentration of the lake water (Peltomaa et al. 2013). As phytoplankton species are the primary producers of biomass in lakes they play important role in variety of food-web structures. Therefore, any shift in their diversity and production has an impact on other aquatic life forms. Changes in environmental conditions, for instance a rise in mean air temperature can influence the stratification of the water column, and affect the domination of cyanobacteria and phytoplankton composition overall (Brookes and Carey 2011; Lürling et al. 2013; Pätynen et al. 2013; De Senerpont Domis et al. 2013). In addition, increase of agricultural and industrial activities can lead to nutrient overenrichment of waters and oxygen depletion at the bottom of the lakes (Paerl and Huisman 2008).

In the palaeolimnological analysis of phytoplankton, it is important to remember that the phytoplankton identified from the pollen slides do not reflect the entire phytoplankton diversity. Phytoplankton species containing sporopollenin are usually resistant to decomposition, while other remains of phytoplankton are not preserved well in lake sediments (Jankovská and Komárek 2000). *Scenedesmus*, *Tetraedron* and *Pediastrum* are most the commons fossil phytoplankton remains (Bellinger and Sigee 2010; Jankovská and Komárek 2000; Komárek and Jankovská 2001; Weckström et al. 2010). Also *Staurastrum* is often preserved because of the impregnation of cell wall material with polyphenolic compounds which confer resistance to bacterial decay (Bellinger and Signee, 2010). A variety of cyanobacteria akinetes are also found in lacustrine sediments, but reason for this can be no strictly associated with eutrophication of the lake and blooming alone, but overwintering or resting into the sediment until suitable conditions for their growth prevail (Fey et al. 2010).

Here we make one of the first attempts to investigate the influence of the key environmental factors on the variability of phytoplankton over the last 14,500 years. The aim of this study is (1) to improve our understanding of how natural temperate aquatic ecosystems (phytoplankton) responded to long-term climate and environmental change during the Late-Glacial and the Holocene, (2) evaluate which environmental factors can influence the domination of specific phytoplankton communities.

Material and Methods

Study area

The fossil phytoplanktons were analysed from a sediment core from Lake Lielais Svētiņu, which is characterised by long sedimentary record and comparatively late human impact (Stivrins et al. 2014; Veski et al. 2012). Lielais Svētiņu (water depth 4 m; 56°45' N; 27°08' E) is located in Rēzekne district of eastern Latvia (Fig. 1) in the Eastern Latvia lowland 13 km east of Lake Lubāns. The present-day topography was formed during the Weichselian glaciation (Zelčs and Markots 2004). The bedrock consists of Devonian dolomite covered by five to ten m thick Quaternary deposits consisting of peat, sand, silt, clay and till (Fig. 1). The Lielais Svētiņu is a drainage lake with an area of 18.8 ha at elevation 96.2 m above the sea level. The catchment area of the Lielais Svētiņu (~12 km^2) is predominantly forested with some fields. The flat shores of the lake are covered by *Betula pendula* and B. *pubescens*, *Picea abies* and *Pinus sylvestris* with scattered stands of *Ulmus laevis*, *U. glabra*, *Tilia cordata*, *Alnus incana A. /glutinosa*, and *Quercus robur*.

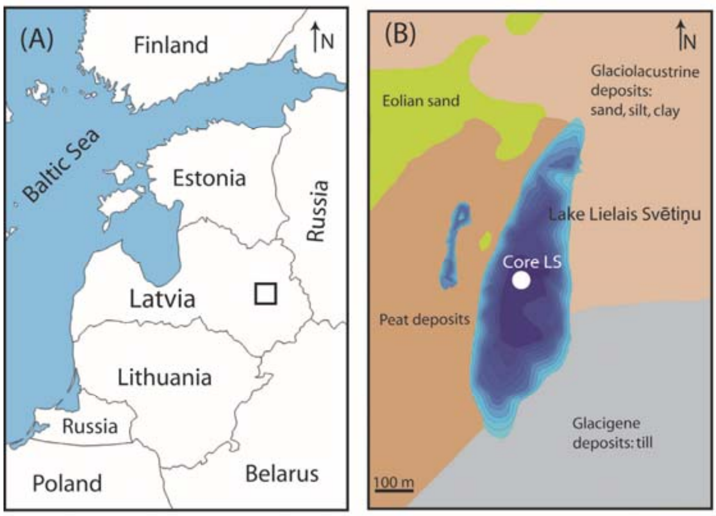

Fig. 1 (A) Map of the eastern Baltic region and location of study area. (B) Map of Quaternary deposits in the study area and coring point in Lake Lielais Svētiņu

The climate in the area is influenced both by the continental climate of Eurasia and by the maritime impact of the Atlantic Ocean and the annual frequency of arctic and sub-polar air masses is fairly high (Avotniece et al. 2010; Draveniece 2009). The mean annual temperature in the nearest city Rēzekne is +5.2 °C, and mean July and December temperatures +16.9 °C and –4.1 °C, respectively (Dauškane et al. 2011).

Coring, sediment description, chronology

Lielais Svētiņu was sampled in March 2009 from ice using a 10-cm diameter Russian type corer. The sediment core was 1,130 cm long. From ice surface 1,535 to 1,160 cm the sediment consists of sand, beige to dark coloured with organic matter, silt and a thin layer of distinctly laminated clay (Veski et al. 2012). Silty gyttja and homogeneous gyttja accumulated from 1,160 to 400 cm (Stivrins et al. 2014). The organic matter content of the Lielais Svētiņu sediment (Fig. 2) was determined by loss-on-ignition (LOI) at 550°C for 4 h and the ignition residue was estimated as the mineral matter. The carbonate content was estimated in terms of the difference between LOI at 900 °C and 550 °C multiplied by 1.36 (Heiri et al. 2001). Measurements were performed on continuous 1-cm thick subsamples and LOI was calculated as percentage of dry weight (Stivrins et al. 2014; Veski et al. 2012).

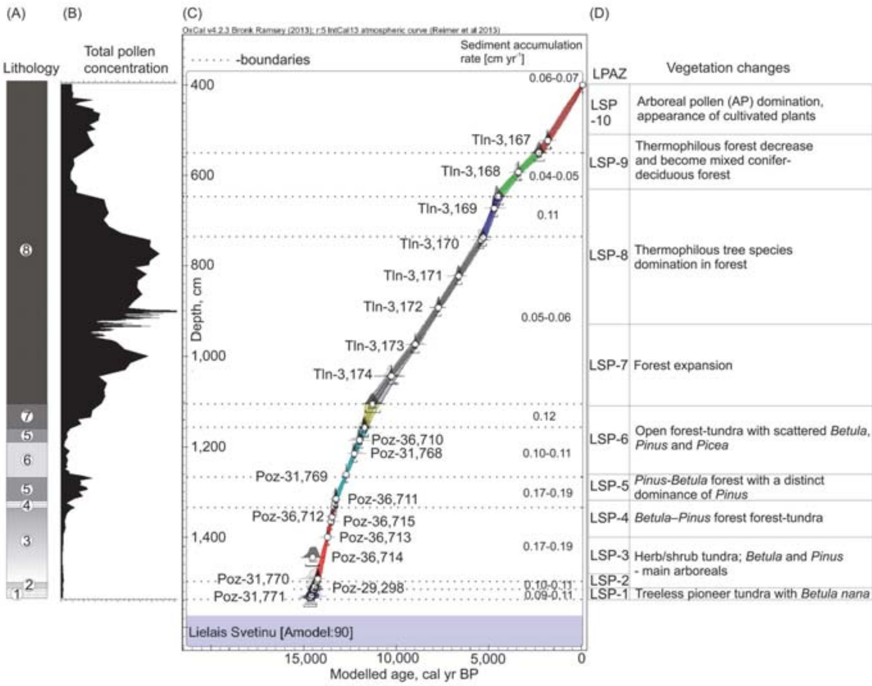

Fig. 2 Bayesian age-depth and sediment accumulation rates across the lithology, total pollen concentration and vegetation changes in the LS profile. (A) Lithology; 1 – compacted sand, 2 – sand with organic matter, 3 – silt, increasingly dark coloured from organic matter towards the upper limit, 4 – laminated clay, 5 – silt with organic matter, 6 – silt, 7 – homogenous silty gyttja, 8 – homogenous gyttja (Stivrins et al. 2014). (B) Total pollen concentration; based on the data published by Veski et al. (2012) and Stivrins et al. (2014). (C) Age-depth model; Poz – Poznań Radiocarbon Laboratory (Poland), Tln – Institute of Geology at Tallinn University of Technology (Estonia), Amodel – agreement index, ○ – μ value of modelled date. (D) Local pollen assemblage zones (LPAZ) and vegetation changes (followed by Stivrins et al. 2014; Veski et al. 2012)

The chronology of the core was established on the basis of a Bayesian age-depth model constructed from with eighteen radiocarbon dates (Electronic Supplementary Material 1). The age-depth model was constructed using the OxCal v. 4.1.2. program (Bronk Ramsey 2008) with a two σ (95.4%) and application of the IntCal13 calibration set (Reimer et al. 2013). The ages in the text refer to calendar years before present (cal yr BP 0=AD 1950).

Microfossil analysis

Subsamples for microfossil analysis (101 samples overall) of known volume (0.5 – 1 cm^3) were treated with 10% HCl, boiled in 10% KOH and then acetolyzed 5 min using standard acetolysis procedures combined with concentrated HF treatment to remove inorganic matter. Known amount of Lycopodium spores were added to estimate microfossil concentration and accumulation rates, and mounted in glycerol. Microfossils of various origins were identified using published literature (Bellinger and Sigee 2010; Jankovská and Komárek 2000; Komárek and Jankovská 2001) and literature listed in Miola (2012). Proportions of phytoplankton and other microfossils were expressed both as accumulation rates (AR) and percentages. AR values were expressed as microfossil type $cm^{-2}yr^{-1}$. The percentage data were used on figures to enable comparison with earlier studies with similar data and were calculated from the total sum of all counted phytoplankton. The percentage proportions of animalia, fungi, charcoal and pyrite are based on the sums of phytoplankton plus the number of the respective remains or particles. Only the AR was used in statistical analyses because percentages here may lead to incorrect interpretation (Wood and Wilmshurst 2013). A microfossil diagram was drawn with TILIA 1.7.16. software (Grimm 2011), and zonation was performed according to the broken-stick model based on binary splitting of the sum-of-squares method using the PSIMPOLL 4.27 software (Bennett 1996). We combined phytoplankton from the same phylum or genus into five major groups – cyanobacteria, *Scenedesmus*, *Pediastrum*, *Botryococcus* and *Coelastrum* – to show general trends of variability and to relate their ARs to environmental factors.

During the microscoping, we found larger quantities of “black spherules” and performed and additional analysis by Scanning Electron Microscope (SEM) to find out their chemical composition. The analysis was carried using Zeiss EVO MA15 SEM in Institute of Geology at Tallinn University of Technology, Estonia.

Indicators of varying environment

We use a range of variables to characterize the biotic and abiotic environmental conditions in the lake and in the catchment. To characterize the sediment, we use the content of mineral matter (MM), carbonate matter (CM) and organic matter (OM). Charcoal >10 µm (Ch_{10}) and charcoal >50 µm (Ch_{50}) indicate fire frequencies in the region. Pyrite (FeS_2) indicates anoxic conditions at the bottom of the lake. In the lacustrine environment, pyrite is formed mostly in the sediments of productive lakes where the oxidation is decreased as a result of microbial decomposition of the organic matter and completely prevailing anoxic conditions (Apolinarska et al. 2011). Barthelmes et al. (2012) reported that pyrite is clear indicator of high decomposition in terrestrial environment. Therefore, we cannot exclude the possibility that the high values of pyrite together with increased MM, F_{hy} and *Glomus* might point to in-wash of decomposed material from the catchment. Mycorrhizal fungus *Glomus* is important markers of episodes of higher downwash in lacustrine sediments (Kołaczek et al. 2013). As the majority of the fungi and fungal hyphae F_{hy} is of strictly local occurrence and can be assumed to belong to terrestrial environment their presence in the lake sediments here indicate local environmental conditions such as inwash from catchment and/or soil erosion (Kołaczek et al. 2013).

Based on the pollen record from Lielais Svētiņu (Stivrins 2014; Veski et al. 2012) we reconstructed the vegetation cover in the surroundings of the lake applying the REVEALS vegetation reconstruction approach (Sugita 2007). We used 23 dominant taxa for which we had the pollen production and fall speed estimates – *Alnus*, *Artemisia*, *Betula*, *Calluna*, *Carpinus*, Cerealia, *Corylus*, *Fagus*, *Filipendula*, *Fraxinus*, *Juniperus*, *Picea*, *Pinus*, *Plantago lanceolata*, *Plantago major/media*, Poaceae, *Quercus*, *Rumex acetosa/acetosella*, *Salix*, *Secale*, *Tilia*, *Ulmus*, *Urtica* – compiled from Broström et al. (2008), Poska et al. (2011) and Mazier et al. (2012). Sum of cover estimates of herbaceous taxa was used as an indicator of landscape openness (OPEN). In addition, we calculated estimates of waterlogging tolerance, drought tolerance and shade tolerance for the vegetation surrounding the lake. For that we used the tolerance values (Niinemets and Valladares 2006) of the 14 trees and shrubs for which we had the REVEALS estimates and used the weighted average values to characterise waterlogging tolerance (W_{tol}), drought tolerance (D_{tol}) and shade tolerance (S_{tol}). When Ch_{10} and Ch_{50} are related to the fire regime in the surroundings of the lake, FeS_2 to anoxic conditions at the bottom of the lake, OPEN, W_{tol}, D_{tol} and S_{tol} reflect the vegetation composition and environmental conditions in the surroundings of the lake and can be assumed to influence the phytoplankton community either directly or indirectly.

To characterize the climate, we used mean winter temperature (T_{win}), and mean summer temperature (T_{sum}) reconstructions from the pollen data from Lielais Svētiņu. The climate parameters were reconstructed with the Finland-Estonia-Sweden-west Russia-Lithuania pollen-climate calibration set (Salonen et al. 2012), using the weighted averaging-partial least squares regression and calibration procedure (ter Braak and Juggins 1993). The pollen samples in the calibration set are lake sediment surface samples collected from the central parts of small to medium-sized lakes Finland, Estonia, Lithuania, west Russia and Sweden (Salonen et al 2014).

Because climate and environment of Late-Glacial (from 14,500 to 11,650 cal yr BP) were extremely different comparing to the Holocene (from 11,650 to -59 cal yr BP) we divided the data into two periods and describe and analysed the periods separately.

Statistical analysis

To study the associations between the fossil phytoplankton communities and reconstructed environmental proxies (Ch_{10}, Ch_{50}, FeS_2, F_{hy}, MM, CM, OM, OPEN, W_{tol}, D_{tol}, S_{tol}, T_{sum}, T_{win}), we used Redundancy Analysis (RDA) (Rao 1973). We used Hellinger transformation of the species data as suggested by Legendre and Gallagher (2001). Ch_{10}, Ch_{50}, FeS_2 and F_{hy} were log-transformed prior to the analysis to unify the variance. To avoid co-linearity, we left out strongly correlated explanatory variables (r>0.85) prior to the analyses (the correlation tables for Late-Glacial and Holocene are given in Electronic Supplementary Material 2). For the Late-Glacial period, the explanatory variables that were included in the analyses were Ch_{10}, Ch_{50}, FeS_2, F_{hy}, MM, OM, OPEN, D_{tol} and T_{sum} (CM, Twin, S_{tol} and W_{tol} were excluded). For the Holocene analysis, Ch_{10}, Ch_{50}, FeS_2, F_{hy}, CM, OM, OPEN, D_{tol}, W_{tol} and T_{sum} were included (and MM, Twin and S_{tol} were excluded). To find the combination of explanatory variables that best explains the variation in phytoplankton data, we used a forward selection procedure until all significant variables were included in the model (command ordistep() from R package "vegan" (Oksanen et al. 2013)).

To study the associations between the accumulation rates of general groups of fossil phytoplankton (cyanobacteria, *Scenedesmus*, *Pediastrum*, *Botryococcus*, *Coelastrum, Tetraedron, Pediastrum*) and environmental proxies (Ch_{10}, Ch_{50}, Fe_2S, F_{hy}, MM, CM, OM, OPEN, W_{tol}, D_{tol}, S_{tol}, T_{sum}, T_{win}), we used Generalized Least

Squares (GLS) analysis. Similar sets of explanatory variables were included in the analyses as in the RDA and variables that were highly correlated with others were excluded. The accumulation rates of cyanobacteria, *Scenedesmus*, *Pediastrum*, *Botryococcus*, *Coelastrum, Tetraedron* and *Pediastrum* were log-transformed prior to the analyses. The associations were tested separately in Late-Glacial period and in the Holocene. For each model, we first tested for the temporal autocorrelation in the residuals. None of the models showed significant residual autocorrelation. We then used a stepwise backward selection procedure with the likelihood ratio test (Zuur et al. 2009) where, at each step, the variable giving the highest p-value was left out of the model until only significant ($P < 0.05$) terms remained. To evaluate the goodness of fit of the GLS model, we calculated squared correlation coefficient (cor^2) between the response variable and the model fitted values. For all statistical analyses, we used the R environment (version 3.0.3) (R Core Team 2014).

Results

Chronology and sediment accumulation rate

Several attempts using all AMS dates failed to give an age-depth model with a model agreement index (A_{model})>60% – the critical value recommended for the reliability of models (Bronk Ramsey 2008). As in the model presented by Veski et al. (2012) date Poz-36714 (Electronic Supplementary Material 1) was a distinct outlier with the lowest individual agreement index in comparison to other dates. Therefore it was excluded from further modelling. A final set of seventeen dates provided a reliable age-depth model with A_{model} = 89.8% (Fig. 2).

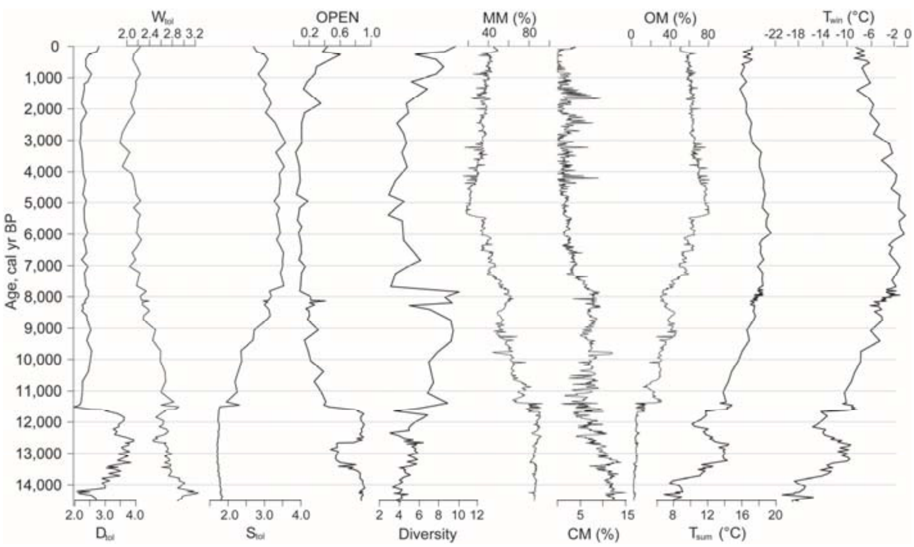

Fig. 3 Comparison of the explanatory variables plotted against time: D_{tol} - drought tolerance; W_{tol} – waterlogging tolerance; D_{tol} – shade tolerance; OPEN – landscape openness; Diversity – phytoplankton diversity (number per sample); MM – mineral matter (%); CM – carbonate matter (%); OM – organic matter (%) (Stivrins et al. 2014; Veski et al. 2012); T_{sum} – mean summer temperature (°C); T_{win} – mean winter temperature (°C)

The results of age-depth modelling (Fig. 2) reveal higher sediment accumulation rate (0.08 – 0.16 $cm^{-2}yr^{-1}$) in Late-Glacial from 14,500 – 11,700 cal yr BP and a constant rate 0.05 – 0.07 $cm^{-2}yr^{-1}$ during the Holocene.

The Late-Glacial is characterized with low organic matter (OM) values (below 7.9%) and mineral matter (MM) values over 90% (Fig. 3). The highest values of carbonate matter (CM) in the sediments were from 14,500 – 8,000 cal yr BP (Fig. 3).

Increase in OM up to 45% appeared at the onset of the Holocene. A clear change in sediment composition was detected at 8,400 – 7,700 cal yr BP when OM had 15% drop, but contrary peak of MM around 8,100 cal yr BP. A sharp rise in OM was recorded around 5,300 cal yr BP.

Microfossils

Nine statistically significant local microfossil assemblage zones were established (Fig. 4, Electronic Supplementary Material 3, 4). The highest AR and percentage values of phytoplankton during Late-Glacial reached in Allerød (13,300 – 12,700 cal yr BP), but overall Late-Glacial (14,500 – 11,700 cal yr BP) is characterized by low phytoplankton AR (Fig. 4). Percentages of microfossil reveal high values of Ch_{10} and F_{hy} from 14,500 – 13,500 cal yr BP and 12,700 – 11,700 cal yr BP, but decrease during the Allerød. *Scenedesmus* and *Tetraedron minimum* were the dominant phytoplanktons. Low AR of *Pediastrum kawraiskyi*, *P. simplex* and *P. boryanum* var. *boryanum* were recorded. In addition, Cladocera had a peak during the Allerød.

Holocene 11,700 – 8,000 cal yr BP had major changes in phytoplankton community with rapid increase in AR (Fig. 4). Dominant taxa were *T. minimum*, *Scenedesmus*, *Botryococcus* and *Glaucospira* (Fig. 4, 5). Later in 8,000 – 2,000 cal yr BP cyanobacteria overwhelmed other algae and had their highest AR and percentage values. A rapid decrease in cyanobacteria and an increase in *Pediastrum*, *Botryococcus* and *Coelastrum* occurred in the last 2,000 – 0 cal yr BP.

SEM analysis revealed that the black spherules consist of S (51%) and Fe (35%) which is known as pyrite (FeS_2) (Fig. 4).

Statistical analyses

The RDA with the Late-Glacial data and the forward selection of environmental variables showed that three variables had significant ($p<0.05$) associations with phytoplankton data (Fig. 6). Only the first RDA axis was significant and it was negatively associated with landscape openness (OPEN) and positively with organic matter content in sediment (OM) and summer temperature (T_{sum}). *Pediastrum kawraiskyi* and *P. boryanum* var. *boryanum* were strongly negatively associated with RDA axis 1 and *Scenedesmus quadricauda* and *Tetraedron minimum* were positively associated with RDA axis 1. The ordination explained 43 % of the variation in the species data.

The RDA with the Holocene data had three significant ordination axes and forward selection showed that five variables had significant associations with phytoplankton data (Fig. 6). The first RDA axis was negatively associated with waterlogging tolerance (W_{tol}) and OPEN in the surrounding landscape and positively associated with OM and T_{sum}. The second RDA axis was strongly negatively associated with charcoal content (Ch_{10}).

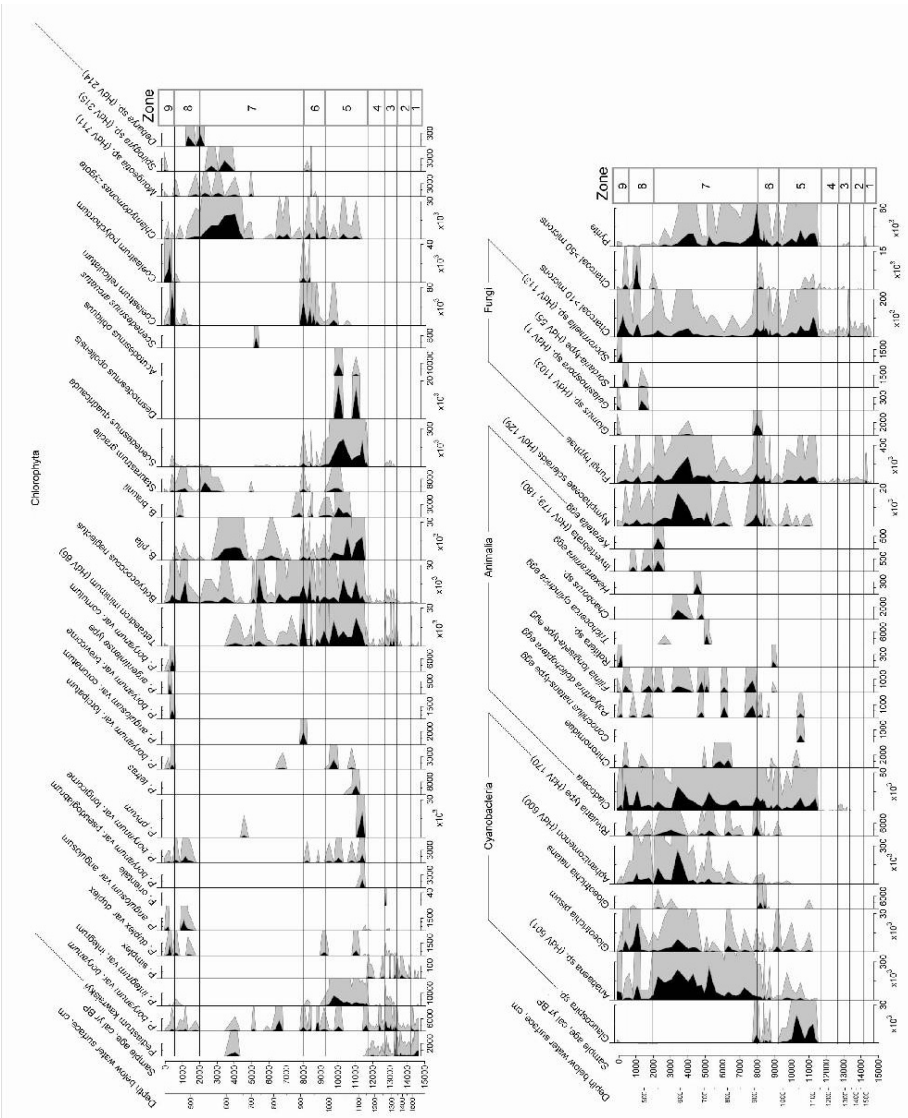

Fig. 4 Microfossil diagram and their accumulation rates from the Lielais Svētiņu profile. Shaded line show ten-fold multiple abundance values

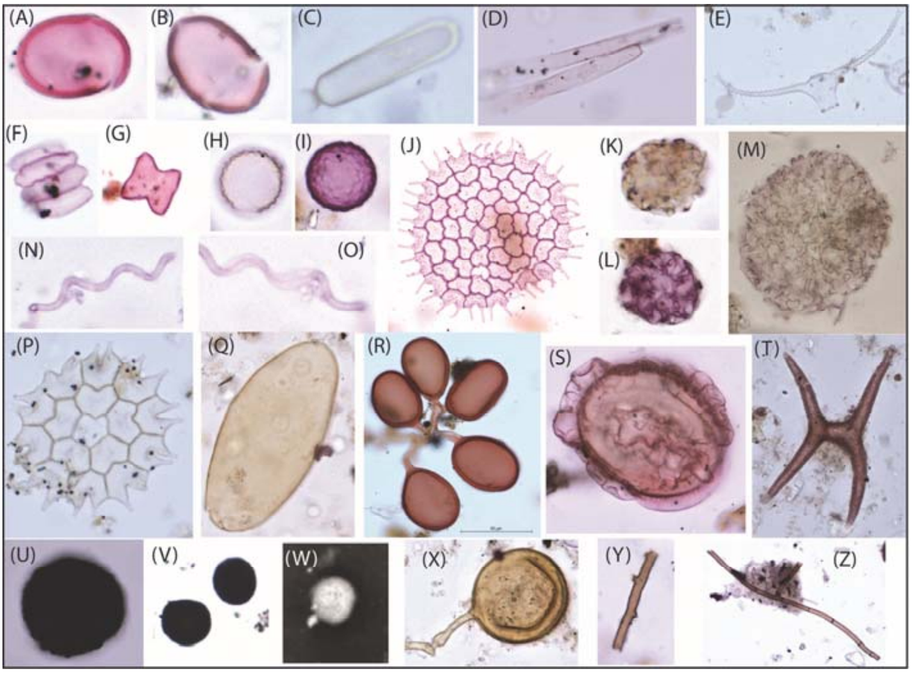

Fig. 5 Selection of microfossils found in sediments of Lielais Svētiņu: (A, B) *Anabaena*; (C) *Aphanizomenon*; (D) *Gloeotrichia pisum*; (E) *Staurastrum gracile*; (F) *Scenedesmus*; (G) *Tetraedron minimum*; (H, I) *Chlamydomonas*; (J) *Pediastrum boryanum* var. *longicorne*; (K, L) *Coelastrum reticulatum*; (M) *Coelastrum polychordum*; (N, O) *Glaucospira*; (P) *Pediastrum boryanum* var. *pseudoglabrum*; (Q) *Spirogyra*; (R, X) *Glomus*; (S) *Filina* resting egg; (T) Nymphaeaceae sclereid; (U, V) Pyrite (light microscope); (W) Pyrite (scanning electro microscope); (Y, Z) Fungi hyphae

Out of the species, *Scenedesmus quadricauda* was strongly negatively and *Aphanizomenon* and *Anabaena* were positively associated with RDA axis 1. *Coelastrum reticulatum* was negatively associated with RDA axis 2. The ordination explained 56 % of the variation in the species data. Also GLS showed all phytoplankton groups were strongly negatively associated with OPEN. OM was positively associated with *Botryococcus* and *Tetraedron*. In addition, *Botryococcus* was strongly positively associated with charcoal (both with Ch_{10} and Ch_{50}) and *Scenedesmus* with T_{sum}.

In the Holocene, OPEN was only associated with cyanobacteria and with *Botryococcus* (in both cases negatively). Ch_{10} was positively associated with several phytoplankton groups (Cyanobacteria, *Coelastrum*, *Botryococcus and Pediastrum*). W_{tol} was positively associated with *Scenedesmus*, *Tetraedron* and *Pediastrum* indicating that these taxa were more abundant in the lake in the periods when the surroundings of the lake were wet (Table 1). *Coelastrum* on the other hand, was positively associated with drought tolerance and T_{sum}, indicating that it was more abundant in dry and warm periods.

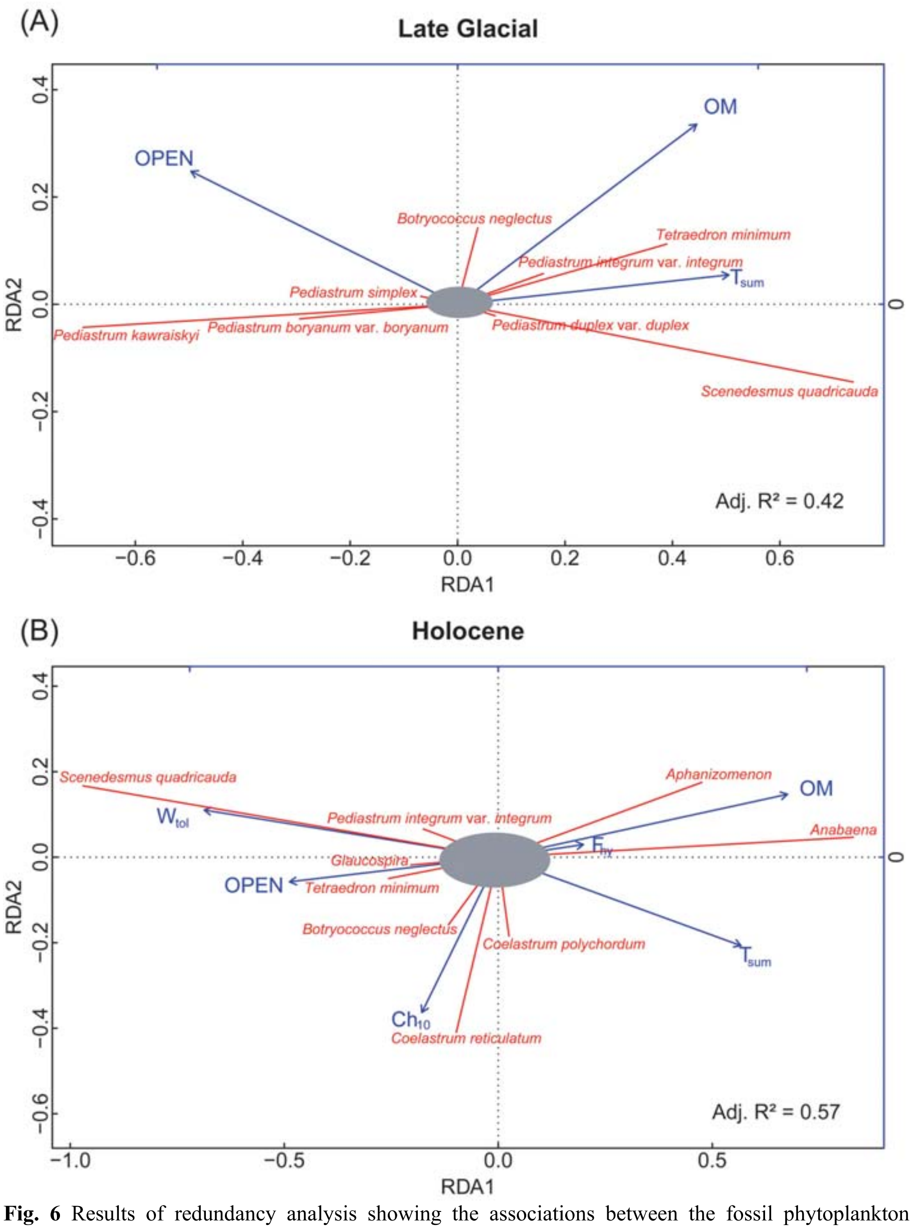

Fig. 6 Results of redundancy analysis showing the associations between the fossil phytoplankton communities and reconstructed environmental proxies (OPEN – landscape openness; OM – organic matter; T_{sum} – mean summer temperature; Ch_{10} – charcoal >10 μm; W_{tol} – waterlogging tolerance; F_{hy} – fungi hyphae) in (A) Late-Glacial and (B) Holocene. Phytoplankton names what are not displayed on plot were located in grey elongated area (*Anabaena*, *Aphanizomenon*, *Rivularia*, *Gloeotrichia pisum*, *G. natans*, *Tetraedron minimum*, *Scenedesmus arcuatus*, *Acutodesmus obliquus*, *Desmodesmus opoliensis*, *Botryococcus neglectus*, *B. pila*, *B. braunii*, *Chlamydomonas*, *Pediastrum boryanum* var. *forcipatum*, *P. boryanum* var. *cornutum*, *P. boryanum* var. *longicorne*, *P. boryanum* var. *pseudoglabrum*, *P. boryanum* var. *brevicorne*, *P. orientale*, *P. tetras*, *P. angulosum* var. *coronatum*, *P. angulosum* var. *angulosum*, *P. argentiniense* type, *P. privum*, *Staurastrum gracile*)

Discussion

Our results show that landscape openness (OPEN) decreases, but organic matter (OM) increases if summer and winter temperature (T_{sum}, T_{win}) rise (Fig. 3). Consequently climate driven factors were strongly related for both time frames. However, climate and vegetation change are interconnected and we can not separate their influence totally, at the same time vegetation dynamics as well as phytoplankton productivity and diversity is related to T_{sum} and T_{win} therefore follows to climatic change. Likewise mean temperature reconstructions were done from the same lake and as surrounding vegetation show response to climatic change that may reflect also to aquatic environment. Besides the effect of air temperature on water temperature has been proven to be even stronger in the case of lakes at lower altitudes (Gallina et al 2013).

Climate improvement by increasing T_{sum} and T_{win} promoted development of stable vegetation in surrounding of Lielais Svētiņu (Veski et al. 2012) and decrease in OPEN during the Bølling-Allerød interstadial (14,500 – 14,050 and 13,050 – 12,850 cal yr BP) (Fig. 3). Additionally terrestrial and aquatic productivity led to accumulation of OM in Lielais Svētiņu (Table 1). Our results, therefore, suggest that the climate warming and following decrease in OPEN, but increase in OM could be one of the main factors behind *Botryococcus*, *Tetraedron*, *Scenedesmus* and *Pediastrum* prevalence in the Lielais Svētiņu during the Late-Glacial (Table 1; Fig. 3, 4). A similar *Pediastrum* appearance in Late-Glacial sediments had been reported by Sarmaja-Korjonen et al. (2006) at the classic Bølling Sø site in Denmark. Wacnik (2009) suggests that rapid increase of *Scenedesmus* and *Tetraedron* is indicator of climate warming and is associated with low nutrient content. The conclusions of Wacnik (2009) are in concordance with our study where *Scenedesmus* is highly positively correlated (0.74) with T_{sum} (Table 1).

Increased mineral matter (MM) and fungal hyphae (F_{hy}), but decrease in T_{win}, T_{sum} during Older Dryas (13,900 – 14,050 cal yr BP) and Younger Dryas (11,650 – 12,859 cal yr BP) indicate that these periods were characterized by cold climate and high soil erosion within the catchment (Fig. 3, 4). In the previous study from the same lake, Veski et al. (2012) demonstrated parallel increase in *Betula* pollen corrosion and redeposition of thermophilous pollen grains during Older and Younger Dryas which supports the idea that soil erosion is the main cause of increase in MM and F_{hy} accumulation. Soil erosion is probably related to the tundra type vegetation (Veski et al. 2012) characterized by low OM, shade tolerance (S_{tol}), high draught tolerance (D_{tol}) and high OPEN (Fig. 3). Lake water was, therefore, probably cold and with low nutrient content. In such oligotrophic conditions *Pediastrum kawraiskyi*, *P. simplex* and *P. integrum* var. *integrum*, *P. orientale* prevailed. This agrees with Weckström et al. (2010) who suggest the occurrence of similar *Pediastrum* community in oligotrophic high-latitude lakes. Furthermore, similar community composition and conditions typical for cold periods have been reported from the Late-Glacial period from Poland and Estonia (Jankovská and Komárek 2000; Kołaczek et al. 2014; Veski 1994; Wacnik 2009).

According to the RDA results W_{tol} – indicating moist and unstable soil conditions in the surroundings of the lake – was positively associated with *Tetraedron minimum*, *Scenedesmus* and *Pediastrum*. In addition to domination of *Tetraedron minimum* and *Scenedesmus*, early Holocene (11,650 – 8,000 cal yr BP) was characterized by high phytoplankton diversity (Fig. 3) suggesting environmental heterogeneity. Similarly to our results, Ralska-Jasiewiczowa et al. (2003) described a rapid increase in *Tetraedron minimum* in Lake Gościąż, Poland. They showed that the abundance of *Tetraedron minimum* was closely associated with $\delta^{18}O$ reflecting climatic improvement at the Younger Dryas and Holocene boundary. Our data support it, as T_{sum} was significantly positively associated with *Tetraedron minimum* (Table 1).

Table 1. Generalized Least Squares models explaining the abundance of major groups of fossil phytoplankton in Lielais Svētiņu. Only significant explanatory variables after backward selection are given together with the sign of association (+/–) and significance level (*** p<0.001; ** p<0.01, * p<0.05). Temporal autocorrelation in the residuals was tested in each of the models but was not significant in any case. Cor^2 shows the squared correlation between the response variable and the model fit

Response variable	Late Glacial (N=46)		Holocene (N=55)	
	Explanatory variables	cor^2	Explanatory variables	cor^2
log(Scenedesmus)	+ T_{sum} *** – OPEN ***	0.74	+ CM * + W_{tol} ***	0.57
log(Botryococcus)	+ Ch_{10} *** + Ch_{50} ** + FeS_2 ** + OM *** – OPEN ***	0.45	+ Ch_{10} * – OM ** – OPEN *	0.27
log(Tetraedron)	+ OM * – OPEN **	0.43	+ FeS_2 ** + T_{sum} *** + W_{tol} ***	0.63
log(Pediastrum)	– D_{tol} * – OPEN ***	0.42	+ Ch_{10} * + W_{tol} ***	0.35
log(Cyanobacteria)			+ Ch_{10} *** + OM *** – OPEN ***	0.85
log(Coelastrum)			+ Ch_{10} *** + T_{sum} ** – OM * + D_{tol} ***	0.51

During the Holocene absence and domination of cyanobacteria was strongly related with climate driven increased T_{win}, T_{sum} and OM, but negatively with OPEN. Paerl and Huisman (2008) point that rising temperatures favour cyanobacteria what gives a competitive advantage at elevated temperatures comparing to other phytoplankton. The domination of cyanobacteria in phytoplankton biomass has been shown to lead to a progressive loss of phytoplankton diversity in temperate lakes (Elliott et al. 2006) and that was also recorded in Lake Lielais Svētiņu (Fig. 3). In addition, a warm, dry and overall stable condition with low water level in lakes was typical during 8,000 – 4,000 cal yr BP (Hammarlund et al. 2003; Muschitiello et al. 2013; Seppä et al. 2009; Sohar and Kalm 2008). As a consequence higher T_{win} and T_{sum} (Fig. 3) could affect water temperature, resulting lower water level and increased lake residence time leading to prolonged periods of water column thermal stratification (De Senerpont Domis et al. 2013). The RDA results display association between cyanobacteria and T_{sum} supporting Pätynen et al. (2014) model of simulations for a boreal lake in Finland and suggest that warming poses a risk of higher cyanobacterial abundances. Our results, therefore possibly agree to various climate change modelling scenarios what predict that if aquatic systems will experience increases in temperature that favour cyanobacteria over other phytoplankton (Brookes and Carey 2011; De Senerpont Domis et al. 2013). Moreover stimulating phytoplankton productivity and stronger thermal stratification can cause a decrease in hypolimnetic oxygen concentrations, enhanced nutrient recycling from sediments, improved conditions for OM preservation and under anoxic conditions benefit production of pyrite (FeS_2) (Fig. 4, 5) (Apolinarska et al. 2011; Battarbee et al. 2010).

Although rising temperatures favour domination of cyanobacteria since 8,000 cal yr BP our record on fossil cyanobacteria show the highest AR occurred from 4,000 – 2,000 cal yr BP (Fig. 4). Possible explanation can be associated with climate variability after 4,000 cal yr BP (Seppä and Poska 2004; Seppä et al. 2009) what followed by decline in temperature, increase in humidity (Stivrins et al. 2014) and eutrophication of the lake via inwash from catchment as suggested by rise in MM, *Glomus* and F_{hy} (Fig. 3, 4, 5). With increasing nutrient inputs and eutrophication of the lake, abundance of cyanobacteria enlarge (Ferber et al. 2004). Elliott (2012) showed that the more nutrient rich the lake is, the greater the response of cyanobacteria populations. Besides, eutrophication is reflected also by rapid increase in *Chlamydomonas* (Fig. 4, 5) known to be abundant in extremely nutrient-rich (eutrophic-hypereutrophic) waters (Reynolds 2006). At the same time, the appearance of *Botryococcus pila* points to the presence of dystrophic waters (Komárek and Jankovská 2001), possibly suggesting spreading peatland in the vicinity of the lake (Fig. 1), but local stand scale presence of conifers (Stivrins et al. 2014) might point to acidification of soils at Lielais Svētiņu. Seemingly previous forcing factors of cyanobacteria – elevated temperature and nutrient loading decreased around 2,000 cal yr BP, thus reduced domination of cyanobacteria. Our results, therefore, support the idea (Brookes and Carey 2011; Elliott et al. 2006; Pätynen et al. 2014) that high nutrient loads and turbidity were more important for the dynamics of cyanobacteria than the increase in temperature alone.

Only in the last two millennia, human activities have disturbed terrestrial environment (Stivrins et al. 2014) and that has led to a shift in phytoplankton community. Previous domination of cyanobacteria was disrupted and taxonomic diversity increased (Fig. 3). Moreover the presence of coprophilous fungi *Sporormiella* and *Sordaria* (Fig. 4) indicates herbivore presence in vicinity of the lake (Baker et al. 2013). Therefore it is possible that agricultural activities – cultivation, grazing, and fertilizing of the land with manure – enriched the lake with additional nutrient supply leading to eutrophication. This is supported by the peaks of *Gloeotrichia pisum*, *Coelastrum reticulatum* and *Coelastrum polychordum* (Fig. 4, 5) – all taxa that are considered to be indicators of eutrophication (Jankovská and Komárek 2000). The results of GLS and RDA show positive relation between *Coelastrum reticulatum* and fire indicator – Ch_{10} supporting the idea that there was considerable pressure of anthropogenic activity and eutrophication on the lake environment during the last two millennia (Jankovská and Komárek 2000; Wacnik 2009). In addition, so far there are no fossil finds of *Coelastrum* in the lake sediments in Estonia we might, therefore, argue that there was a northern distribution limit of *Coelastrum reticulatum* and *Coelastrum polychordum*.

Conclusions

Our study indicates that the phytoplankton community and diversity changed along with changes in terrestrial environment over the last 14,500 years. Two major time frames – Late-Glacial and Holocene were distinguished to evaluate possible influencing factors. Rarefaction analysis showed that higher phytoplankton diversity in the Late-Glacial was during the warm Bølling-Allerød interstadial, but in the Holocene during the cooler early and late Holocene. Based on statistical results mean air temperature and landscape openness were significant environmental explanatory variables affecting dynamics of phytoplankton community over the last 14,500 cal yr BP in eastern Latvia. In addition, waterlogging tolerance showing moist soil in surrounding was significant factor for *Pediastrum*, *Scenedesmus* and *Tetraedron minimum*. During the Holocene absence and domination of cyanobacteria was strongly related with climate driven increased mean air temperature and organic matter in the lake, but negatively with landscape openness. Our results illustrate that if aquatic systems experience increases in temperature that favour cyanobacteria over other phytoplankton. However the highest biomass of cyanobacteria reached from 4,000 – 2,000 cal yr BP when transformation in climate and environmental conditions accelerated high nutrient loads in Lielais Svētiņu. Therefore raise in nutrient loads were more important for the dynamics of cyanobacteria than the increase in temperature alone. In addition, phytoplankton composition and microfossils permit to specify length of transition from Holocene Thermal Maximum to late Holocene what started with eutrophication-hypereutrophication of the lake at 4,000 cal yr BP and terminate with returning to lower nutrient status at 2,000 cal yr BP.

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Paper VI Stivrins, N., Brown, A., Veski, S., Ratniece, V., Heinsalu, A., Austin, J., Liiv, M., Ceriņa, A. Palaeoenvironmental evidence for the impact of the crusades on the local and regional environment of medieval (13th–16th century) northern Latvia, eastern Baltic. The Holocene (submitted manuscript).

Palaeoenvironmental evidence for the impact of the crusades on the local and regional environment of medieval (13th–16th century) northern Latvia, eastern Baltic

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Abstract

This paper evaluates the impact of the northern crusades on the landscape and environment of northern Latvia between the 13th–16th centuries (medieval Livonia). The crusades replaced tribal societies in the eastern Baltic with a religious state (Ordenstaat) run by the military orders and their allies, accompanied by significant social, cultural and economic developments. These changes have previously received little consideration in palaeoenvironmental studies of past land-use in the eastern Baltic region, but are fundamental to understanding the development and expansion of a European Christian identity. Sediment cores from Lake Trikātas, located adjacent to a medieval castle and settlement, were studied using pollen, macrofossils, loss-on-ignition and magnetic susceptibility. Our results show that despite continuous agricultural land-use from 500 BC, the local landscape was still densely wooded until the start of the crusades in AD 1198. Colonisation followed the crusades, though in Livonia this occurred on a much smaller scale than in the rest of the Ordenstaat; Trikāta is atypical is showing significant impact following the crusades with many other palaeoenvironmental studies only revealing more limited impact from the 14th century and later. Subsequent wars and changes in political control in the Post-medieval period had little apparent effect on agricultural land-use, with the period from AD 1800–1900 date representing the height of agricultural land-use in northern Latvia.

Keywords
The crusades, human impact, pollen, macrofossils, Iron Age, Latvia

Introduction

The medieval period in the eastern Baltic (AD 1198–1561) is dominated by the crusades, a holy war led by the military orders and bishops that over the course of the 13th century conquered modern-day Estonia, Latvia and western Lithuania with the aim of converting indigenous pagan tribal societies to Christianity. The conquest and subsequent colonisation of former tribal territories resulted in significant changes to the ownership organisation and administration of the landscape, with subsequent changes in patterns of land-use over the 13th–16th centuries (Brown and Pluskowski, 2014). The crusades was followed by the development of towns and rural settlements, secured by heavily fortified castles, and accompanied by economic expansion and the development of trading and provisioning networks, exemplified by the growth of the Hanseatic League from the 13th century (Turnbill, 2004; Sillasoo and Hiie, 2007). Previous studies of the impact of crusading have focused largely on documentary sources with little consideration of the potential of the palaeoenvironmental record. Documentary sources, often in the form of inventories, demonstrate the diversity and intensity of resource exploitation, but are largely 14th century and later in date and lack the longer-term chronological perspective of the palaeoenvironmental record. Although palaeoenvironmental studies over the last two decades have greatly contributed to our knowledge on vegetation change in Latvia (Amon et al., 2014; Kalnina et al., 2004; Kangur et al., 2009; Kušķe et al., 2010; Ozola et al., 2010; Stivrins et al., 2014), existing research has almost entirely focused on natural long-term vegetation dynamics, with less research on environmental changes occurring during more recent periods of significant and rapid social and cultural change. Thus far there are only a few well-dated pollen sequences from northern Latvia (Terasmaa et al., 2013; Stivrins et al., in press). Moreover the crusades in northern Latvia are poorly supported by documentary sources and archaeological investigations. Multi-proxy palaeoenvironmental studies therefore play a significant role in understanding changing patterns of land-use and environmental impact over the several centuries before, during and after the medieval period.

The present study aims to 1) determine whether the crusades result in an increasing anthropogenic impact on the landscape – particularly within the area around Lake Trikātas where tribal grouping very quickly submitted to the rule of the Order and 2) assess the effect of human activities on local and regional terrestrial environment before and after the conquest of the crusades.

Study Area

Sampling site

Lake Trikātas (water depth 4 m; 57°32'N, 25°42'E) is situated in northern Latvia (Figure 1) in the north Vidzeme lowland 17 km east of Valmiera at an elevation of 50 m above sea level. The surface area of the lake is 13 ha. The lake is located in a valley (25 m deep) with an outflow connected with the River Abuls on the western side. The modern vegetation cover along the lake margins and River Abuls comprises *Alnus incana/glutinosa*, *Betula pendula/pubescens*, *Picea abies*, *Pinus sylvestris*, *Quercus robur*. The surrounding landscape comprises a mixture of cultivated land and pasture (Figure 1) overlaying sandy and podzolic soils (Kasparinskis and Nikodemus, 2012). The quaternary glacial till and alluvial deposits at Trikātas overlie the sandstone bedrock and today's topography was largely formed during the Weichselian glaciation and deglaciation (Zelčs and Markots, 2004; Zelčs et al., 2011).

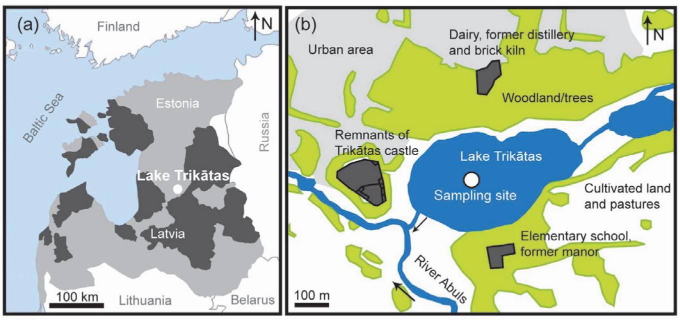

Figure 1. Study area: (a) location of study site in Livonia in eastern Baltic area, black coloured – territories of bishops, grey coloured – territories of Teutonic Order, (b) Lake Trikātas, coring site and setting around the lake.

Lake Trikātas is located in the boreo-nemoral ecotonal zone and climate is continental with mean annual precipitation of 700–800 mm and mean January and July temperatures of –6 °C and +16.5 °C, respectively. The ruins of Trikāta Castle lie on a hilly plateau to the west of the lake with an elementary school and former manor on the valley edge overlooking the southern shore and a former distillery and working dairy overlooking the northern shore (Figure 1). The immediate surroundings of the castle appear to hold no archaeological significance other than the medieval church of St. John to the east of the castle, and extensive agricultural field systems.

History and archaeology of Trikāta

There are a number of historical sources related to Trikāta (German Trikaten) (Caune and Ose, 2004; Radiņš, 1996; Urtāns, 1991). The earliest mention of Trikāta appears in the chronicle of Henry of Livonia in AD 1208, as the location of one of two strongholds ruled over by a local Latgalian chieftain (Tamm, 2011: 450). The crusades in Livonia began with the conquest of the Livs and Latgalians (AD 1198–1227) by the armies of the Bishops and the Sword Brothers, followed by the conquest of Estonia (AD 1208–1227) and partially successful crusades in Curonia (western Latvia) (AD 1219–1290). Following their defeat at the Battle of Saule (AD 1236) the Sword Brothers were merged into the Teutonic Order, known thereafter as the Livonian Order. The stone castle, constructed by the Livonian Order on high ground adjacent to the lake, may have been built on the earlier Iron Age stronghold through there have been no archaeological excavations to confirm this. There have been no archaeological surveys in the immediate hinterland of the castle; the only stray find, found near the lake, was identified as a brooch of third century AD date. There are no direct sources to confirm the date of construction of the castle, but it is considered to predate the formation of the Parish of St. John in AD 1282–1287. Additional documentary sources highlight Trikāta as one of a number of castles listed as corn houses, emphasising their function in the collection, storage and redistribution of agricultural produce (Caune and Ose, 2004). During the medieval period Trikāta formed part of a network of subsidiary castles in the Cēsis commandery (Caune and Ose, 2004). The castle was heavily damaged during the Livonian Wars (AD 1558–1583), and following the secularisation of the Order (AD 1561), many of the Order's documents were destroyed or spread across Europe (Brown and Pluskowski, 2014). As a consequence there is a lack of documentary or archaeological information on Trikāta; any former traces of medieval agricultural land use are likely to have been eroded by continued ploughing over the last half millennia.

Materials and methods

Fieldwork to obtain the core sample from Lake Trikātas was conducted from the ice-covered surface in March 2012 using a 1 m-long Russian-type corer with an 8 m-long sediment sequence recovered at the deepest point of the lake (Figure 1). Samples were documented, packed into film-wrapped 1 m plastic semi-tubes and transported to the laboratory for further analysis. Lithology and sediment features were described in the field.

The organic matter content of the sediment was determined for consecutive 2 cm subsamples by loss-on-ignition at 550 °C for four hours with the ignition residue representing the mineral matter content. Magnetic susceptibility was measured with a Bartington MS2E meter (Nowaczyk, 2001).

Samples for pollen analysis (36 subsamples) of known volume (1 cm^3) and thickness (1 cm) were processed using standard procedures (Berglund and Ralska-Jasiewiczowa, 1986). Known quantities of *Lycopodium* spores were added to each sample to allow calculation of pollen concentrations (Stockmarr, 1971) and are a measure that is not dependent on the changes in sediment redeposition (Seppä and Hicks, 2006). Approximately 1000 terrestrial pollen per sample were counted and identified to the lowest possible taxonomic level using the reference collection at the Institute of Geology at Tallinn University of Technology and published pollen keys. The percentage of dry-land taxa was estimated using arboreal and non-arboreal pollen sums (excluding sporomorphs of aquatic and wetland plants). Counts of spores were calculated as percentages of the total sum of terrestrial pollen. Sum of cultural indicators were grouped according to Behre (1988) and Gaillard (2007). Microscopic charcoal content in pollen slides were estimated as in Finsinger et al. (2008). Plant macrofossil analysis followed Birks (2001). At least 50 cm^3 of sediment was wet-sieved on a 0.25 mm mesh. Retained material of 65 samples on the sieves was examined using a light microscope and identified using literature on plant macrofossils (Rasiņš, 1954; Velichkevich and Zastawniak, 2006, 2008). Pollen and macrofossil diagrams were compiled using TILIA 1.7.16 (Grimm, 2012). As the focus of this article concerns the impact of changing patterns of land-use following the crusades In order to place the palaeobotanical data within a cultural context, the pollen and plant macrofossil diagrams were divided according to established Latvian archaeological periods: Bronze Age 1200–500 BC, Early Iron Age 500 BC–AD 400, Middle Iron Age AD 400–800, Late Iron Age AD 800–1200, Medieval time AD 1200–1550, Post-Medieval AD 1550–1850 and Modern AD 1850–present (Graudonis, 2001; Vasks et al., 1999).

The chronology of the core was established on the basis of a Bayesian age-depth model constructed from six AMS ^{14}C dates. The dated material, all of terrestrial origin, was processed at the Scottish Universities Environmental Research Centre, United Kingdom (GU) and the Poznan radiocarbon laboratory, Poland (Poz). In addition seven gyttja bulk material was dated in Institute of Geology, Tallinn University of Technology, Estonia (Tln) (Table 1). Radiocarbon dates were converted to calendar years using the IntCal13 calibration dataset (Reimer et al., 2013) and Clam 2.2 programme deposition model (Blaauw, 2010) with a 95.4% of confidence level.

Table 1. Radiocarbon ages for Lake Trikātas sediment core.

Depth, cm	Laboratory code	14C date	Calibrated age (cal yr BP) 2σ	Material dated	Remarks
450	GU-27675	1115±35	1090 - 935	Bulk gyttja	Hard water error; excluded
475	GU-27676	1200±35	1190 - 1050	Bulk gyttja	Hard water error; excluded
477	GU-29839	1918±26	1930 - 1820	*Spergula arvensis*	Hard water error; excluded
481,5	GU-29840	158±26	230 - 165	*Ranunculus* leaf fragments	
483	Poz-61639	175±30	225 - 135	Wood	
500	GU-27677	1535±35	1525 - 1350	Bulk gyttja	Hard water error; excluded
525	GU-27678	1735±35	1720 - 1555	Bulk gyttja	Hard water error; excluded
545	Poz-61640	915±30	920 - 760	*Picea abies* needles and fragment of seed wing	
550	GU-27679	2800±35	2990 - 2840	Bulk gyttja	Hard water error; excluded
575	GU-27680	2840±35	3060 - 2860	Bulk gyttja	Hard water error; excluded
577	Poz-61641	1345±30	1310 - 1240	*Picea abies* needle fragment	
689	Poz-61642	2485±30	2725 - 2440	Wood	
723	Poz-61643	2990±30	3250 - 3070	Wood	

Results

Sediment description, chronology and sediment accumulation rates

The Lake Trikātas sediments (Figure 2) consist of silty and homogenous gyttja with visible variations in colour considered to reflect different sedimentation conditions and changes in terrestrial environment.

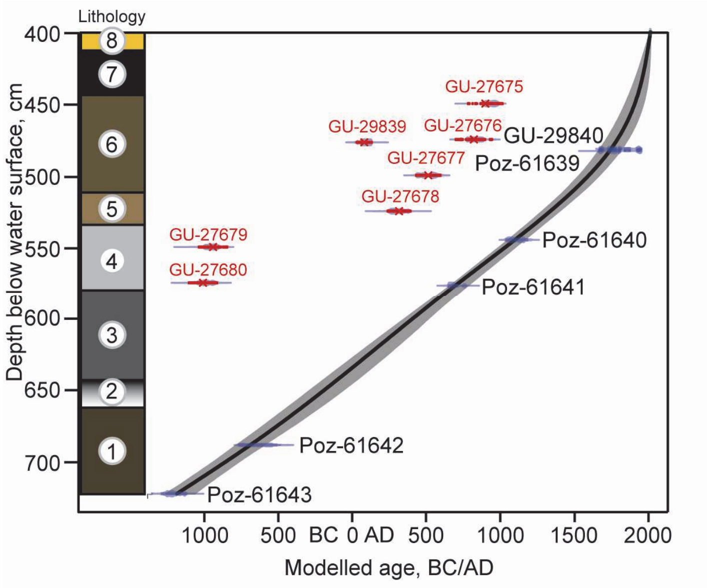

Figure 2. Lithostratigraphy and age-depth model for Lake Trikātas sediment sequence. The grey area represents the range of the modelled ages at 2 sigma. The black graphs show the probability distribution of the calibrated radiocarbon dates. Contaminated bulk dates (black graphs off the age-depth line) were excluded from the age-depth model. Lithology: 1 – gyttja, silty, calcareous, yellow, 2 – gyttja, silty, calcareous, black, 3 – gyttja, silty, calcareous, dark, 4 – gyttja, silty, calcareous, light brown, 5 – gyttja, silty, calcareous, light grey, 6 – gyttja, silty, calcareous, dark grey brown, 7 – gyttja, silty, calcareous, transition, 8 – gyttja, silty, homogenous, dark brown.

Organic matter content (Figure 3(f)) show minor fluctuations with decreasing organic matter content from 1145 BC (40%) to AD 1100 (25%). Following two distinct peaks from AD 1110–1340 and AD 1560–1790 the mineral matter content of the sediment increases significantly (Figure 3(e)). Magnetic susceptibility shows significant fluctuations in value, but with exceptional peaks at 1000 and 900 BC and AD 300 and 600. There is an additional increase in magnetic susceptibility from AD 1400, with values declining significantly at and after AD 1900 (Figure 3(f)). Five peaks of quartz grains were recorded at AD 400, 1100, 1250, 1500 and 1850.

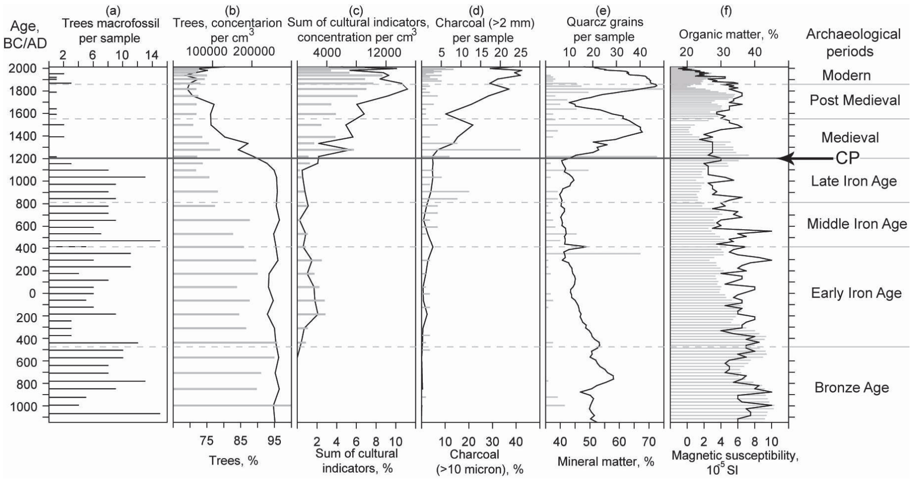

Figure 3. Comparison of main results obtained from Lake Trikātas plotted against time. Bars: (a) tree macrofossil per sample, (b) tree pollen concentration per cm^3, (c) sum of cultural pollen indicators concentration per cm^3, (d) macrocharcoal (>2 mm) number of remains per sample, (e) quartz grain number per sample, (f) organic matter percentages. Solid line: (b) tree pollen percentages, (c) sum of cultural pollen indicators, percentages, (d) microcharcoal (>10 μ), percentages, (e) mineral matter content, percentages, (f) magnetic susceptibility, 10^{-5} SI.

In the course of the Weichselian glaciation large volumes of carbonaceous sediment were brought from Estonia and deposited over most of Latvia in the process of deglaciation (Zelčs et al., 2011). Accordingly, carbonaceous material may be present in most lake sediments, contaminating bulk samples and causing reservoir and hard water effects that produce anomalously old radiocarbon ages (Poska and Saarse, 2002). Moreover, our results showed that the error from bulk dating can be more than 1500 years (Figure 2); AMS dating of organics of terrestrial origin is highly recommended in a future studies carried out on lake sediments in Latvia. The applied age-depth model (Figure 2) based on AMS dates of terrestrial macrofossils showed that the average sediment accumulation rate was 0.07 mm yr^{-1} from 1145 BC–AD 1000, 0.09 mm yr^{-1} from AD 1000–1500 increasing rapidly thereafter up to 0.7 mm yr^{-1}.

Pollen and macrofossils

During the Bronze Age (1200–500 BC): arboreal pollen is dominated by *Picea* (20%), *Pinus* (15%), *Betula* (30%) and *Alnus* (20%) (Figure 4). Other secondary arboreal pollen includes *Quercus* (5%), *Corylus* (5%) and *Tilia* (4%). The plant macrofossil record includes remains of several tree taxa and species (*Betula* sect Albae, *Alnus* *glutinosa*, *Alnus incana* and *Picea abies*) dominant throughout the Bronze Age (Figure 5).

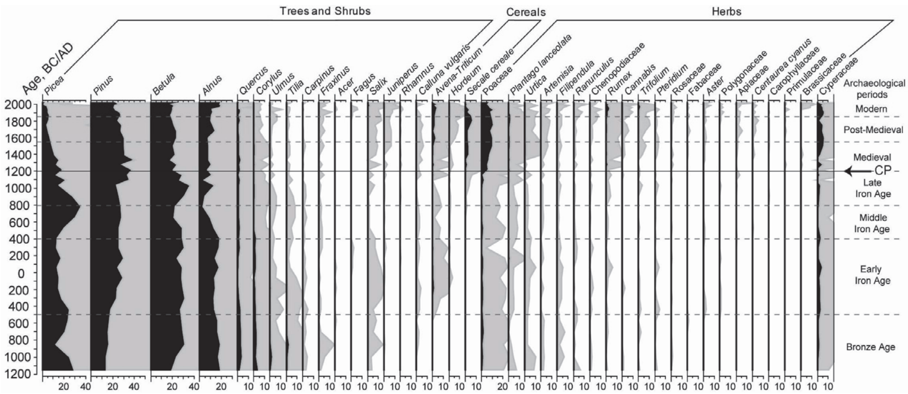

Figure 4. Diagram of selected pollen (percentages) from Lake Trikātas. The grey area shows the multiplication by 10. CP marks the onset of the Crusades.

Early Iron Age (500 BC–AD 400): the first cereal grains of *Avena-Triticum* and *Hordeum* were recorded from 500 and 100 BC respectively (Figure 4). Only *Avena-Triticum* had a continuous pollen curve since its first appearance. Non arboreal pollen values were low throughout the Early Iron Age. Values of *Alnus* and *Betula* were constant at 20% and 30% respectively. *Pinus* values increase from 15% up to 20% towards AD 400. *Picea* decreased from 25% at 400 BC to 15% at 200 BC onwards. Similar trends have been recorded in macrofossil data (Figure 5) where *Betula* sect Albae stayed at the same level during the Early Iron Age. Remains of *Alnus glutinosa* and *Alnus incana* decreased notably however. Microcharcoal and macro charcoal presence in a lake sediment continuously increased from 500 BC.

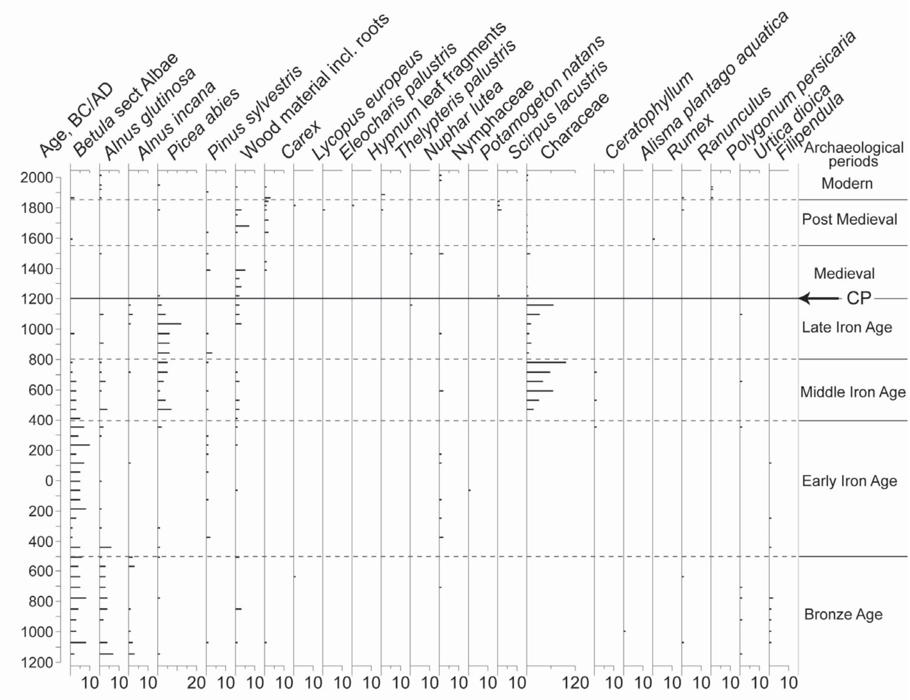

Figure 5. The macroremains found in the lake Trikātas sediment. Values - number of remains per sample. CP marks the onset of the Crusades.

Middle Iron Age (AD 400–800): characterized by an increase in pollen and plant macrofossils of *Picea abies*, with pollen frquences rising sharply from 15% to 40% through the zone (Figure 4, 5) (Figure 5). *Alnus* and *Betula* decreased down to 5% and 25% at AD 700. *Betula* sect Albae decreases towards the end of the zone. *Rumex*, *Urtica*, *Plantago lanceolata* and Poaceae dominated within non arboreal pollen. Grains of *Secale cereale* occur intermittently at low values from AD 750. Frequencies of macrocharcoal increased from AD 600 (Figure 3(d)). Tree pollen concentration minor decrease started from AD 700.

Late Iron Age (AD 800–1200): marks an abrupt decrease in *Picea* from 40% to 15% by AD 1000. Macrofossils of *Picea abies* show high frequencies but decrease only after AD 1100 (Figure 5). *Betula* values increase from AD 800, peaking by AD 1050 but declining thereafter with values for *Pinus* increasing towards the end of the zone.

Medieval (AD 1200–1550): abrupt changes in vegetation occur from ca. AD 1200 with increase values for Poaceae, *Artemisia*, *Rumex*, *Calluna vulgaris* and cereal grains of *Avena-Triticum*, *Secale cereale* and *Hordeum* (Figure 3(c), 4). At the same time tree macrofossils diminish (Figure 3(a), 5), although pollen frequencies of most arboreal taxa remain constant with only *Picea* decling. The highest concentrations of macroscopic charcoal occur ca. AD 1250.

Post-Medieval (AD 1550–1850) indicate the highest values of *Secale cereale* (10%) ca. AD 1800 (Figure 4). Pollen and macrofossils of *Picea* persist at low values throughout the Post-medieval (Figure 4, 5) with consistent values for other arboreal taxa and only a minor increase of *Alnus* ca. AD 1700.

Modern times (AD 1850–present): show decrease in *Secale cereale*, but increase in *Avena-Triticum*, *Rumex*, *Trifolium*, and *Alnus* pollen (Figure 4). Tree macrofossils were recovered in low frequencies (Figure 5).

Discussion

Prehistory (1200 BC–AD 1200)

The palaeovegetation records from Lake Trikātas (Figure 4, 5) indicate a heavily wooded landscape in the vicinity of the lake, with mixed *Betula*, *Picea*, *Pinus*, *Quercus* and *Tilia* woodland dominating until ca. 500 BC. The homogeneity of the sediments, consistently high values of arboreal pollen and organic matter content suggest there is little evidence for human interference in the surrounding landscape (Figure 3(f), 4, 5). There are increasing signs of human impact from 500 BC, with a continuous increase in charcoal particles (Figure 3(d)) and decrease in macrofossils of *Alnus glutinosa* and *Alnus incana* from 500 BC (Figure 5), the latter associated in many diagrams across the eastern Baltic, and more widely in Poland, with increasing human impact and opening of the landscape (Reitalu et al., 2013; Saarse et al., 2010; Wacnik et al., 2014). *Alnus* possibly grew on the most fertile soils surrounding the lake, cleared by humans for agriculture.

The beginning of continuous cereal cultivation is indicated by consistent values for *Avena-Triticum* pollen from 500 BC and *Hordeum* pollen since 100 BC (Figure 4). The highest values of cultural indicators (Figure (3(c)) during prehistory date from 200 BC–AD 300 and because there is no supporting archaeological evidence for increasing settlement activity then palaeo data is even more important in providing clear evidence for an increase in the intensity of land-use. The absence of winter-cereals could indicate a certain emphasis on stock breeding. At Lake Trikātas an agricultural based economy clearly occurs later reflecting the variation of practices within and between Baltic regions where at least 4000 year cultivation history is observed close to settlement centres and much later in peripheral areas (Heikkilä and Seppä, 2010; Heinsalu and Veski, 2010; Poska et al., 2004; Puusepp and Kangur, 2010; Reitalu et al., 2013; Kalnina et al., 2004; Vasks et al., 1999).

In addition clearance of woodland for agricultural purposes, pasture and meadows may result in favourable growth condition for certain competitively superior arboreal taxa like *Picea abies* (Figure 4, 5) and to suppress other taxa (Reitalu et al., 2013). In addition Poska et al. (2004) suggest that an increase in *Picea abies* accompanied by higher values for herb pollen and charcoal frequencies point to the development and intensive use of a pastoral landscape. In addition, because pollen records in lake sediments represent both regional and local vegetation, plant macrofossils can provide information on the vegetation growing directly around the sedimentary basin (Amon et al., 2014; Birks and Birks, 2006). In this sense the subsequent decline of *Picea* pollen may reflect *Picea* clearance regionally from AD 800, although macrofossils of *Picea*, reflecting its local presence around the lake, decline much later by AD 1200 (Figure 4, 5). These changes may be related not only to clearance of woodland (Figure 3(a), 3(b)), but also to the growing need for timber for construction and fuel. More active lake shore clearance of trees could favour erosion of slopes accounting for the continuous abundance of quartz grains in the lake sediments (Figure 3(e)). Episode of arable intensification suggest that continuous land-use and permanent settlement were established since ca. 500 BC.

Medieval period (AD 1200–1550)

Major changes in vegetation occur from AD 1200 with the increase in cultivated cereals (*Secale cereale*, *Hordeum*, *Avena-Triticum*) and charcoal accompanied by the continued decline in surrounding woodland (Figure 3(a)) – clear evidence of landscape modification. Furthermore, the increase in charcoal correlates with an increase in the mineral matter and magnetic susceptibility (Figure 3(f)) that implies woodland clearance and enhanced agricultural activity resulting in increased soil erosion rates within the lake catchment. The abrupt increase from AD 1200 in pollen of cultivated land, increasing macrocharcoal frequencies and inclusion of quartz grains (Figure 3(d)), suggest a causal link between intensifying land-use and the conquest of the Latvia by the Order of the Sword Brothers (1209-1227). Furthermore the increase in cultural indicators following the crusades indicates a degree of stability in land-use, reflected in the formation of the Parish of St. John ca. AD 1282–1287.

High macrocharcoal frequencies, wood material including roots, and a decrease in pollen and plant macrofossils of trees (Figure 3(a), 4, 5) imply a massive opening of the landscape around the lake. The decline in woodland is accompanied by a significant increase in non-arboreal pollen types indicative of disturbed, grazed and cultivated ground, notably *Artemisia*, *Aster*-type, Chenopodiaceae, *Rumex* type, *Trifolium*, *Centaurea cyanus* and cereal pollen. This increase in these pollen taxa strongly implies the development of a mosaic pattern of land-use. *Centaurea cyanus*, in particular, is a weed strongly associated with cereal cultivation and has been argued to reflect the presence of permanent fields (Poska et al., 2004; Vuorela, 1986). The presence of winter and spring cereals suggests the development of a rotational crop regime. During medieval times, the three-field system was established with a rotating cultivation of winter crop, summer crop and fallow land (Enters et al., 2008). Cultivated land would be fallow, and presumably could be under graze, and animal manure would have been an important source of nutrient to cycle back into the fields. Higher proportions of *Juniperus* pollen have previously been taken as indicators of the expansion of dry meadow habitats (Veski et al. 2005), that in the context of the Lake Trikātas study suggest meadows could have formed an equal or greater proportion of farmland surrounding the lake.

The 13th century increase in cereal cultivation at Trikāta differs from other palynological studies from southern Estonia and northern Latvia that generally only show an increase in cereal cultivation a century after the crusades, of 14th century and later date. The study of Veski et al. (2005) at Lake Rõuge Tõugjärv (southern Estonia) shows agricultural activity from AD 1350, with pollen analysis from Äriküla, near the Order Castle at Karksi, showing a similar 14th century increase in cereal cultivation. Three pollen sequences from peatlands around Cēsis, central Latvia (former German Wenden and the Head Quarter of the Livonian Order) show a similar pattern of agricultural intensification from the mid-14th century and later (Brown and Pluskowski, 2014). However, a pollen sequence from adjacent to the Iron Age lake settlement and medieval castle at Āriaši, south-east of Cēsis, shows a decline in agricultural land-use from the start of the medieval period, only increasing again during the 14th century (Stivrins et al., in press), perhaps linked with the construction of the castle during the first half of the 14th century. The palynological sequences from southern Estonia and northern Latvia reflect more broadly the history of land-use across medieval Livonia. The crusades in the eastern Baltic differ significantly from Prussia (present-day north-east Poland) where the conquests of the Teutonic Order were accompanied by significant colonisation, evident by the numerous rural and urban foundations (Pluskowski, 2012). Colonization in Livonia was largely restricted to the major urban centres, such as Riga, with little colonization of the rural hinterlands, with native populations continuing to follow indigenous patterns of land-use (e.g. Mugurēvičs, 2008). Intensification in agricultural activity during the 14th century appears to have occurred in the context of the growing significance of the Hanseatic League and the development of the manorial system, creating an increased demand for agricultural produce (Raun, 2002; Kala, 2005). However there would have been a requirement to produce cereals to support the castles and new urban centres appearing across Livonia during the 13th century. Documentary sources from the 14th century refer to Trikāta as a cornhouse, responsible for the collection, storage and redistribution of agricultural produce. It is probable that the castle and its hinterland performed a critical function during the initial decades of the crusades in producing and supplying agricultural surplus to castles located within those more unstable zones of Livonia (e.g. Curonia). The staples of primary importance for cultivation and consumption correspond with written sources in Latvia and Estonia highlighting the dominance of *Avena-Triticum*, *Hordeum* and *Secale cereale* associated with the Hanseatic League (Sillassoo and Hiie, 2007).

Post-medieval and Modern (AD 1550–present)

The Livonian Order was secularised in 1561, representing the transition between medieval and Post-medieval periods, with Livonia subsequently coming under Polish and Swedish control during the late 16th and 17th centuries. Interestingly there is a reduction in quantities of macroscopic and microscopic charcoal ca. AD 1550–1600 (Figure 3(d)), indicating a reduction of local and regional fire frequency, perhaps reflecting instability in the landscape or a reduction in population. However, this theory is not supported by the levels of cultural indicator pollen that suggest continuity in agricultural land-use.

This is supported by the further development of manors during the 17^{th} century, the first established in AD 1654, with more than 13 in the parish of Trikāta (Enzeliņš, 1931). Extensive agriculture occurred after AD 1750 with a significant increase in cereals. The period from AD 1800–1900 represents the height of agricultural land-use in northern Latvia (Figure 3(c)). Moreover livestock farming developed alongside cereal cultivation. In AD 1828 a sheep farm was established surrounding Trikāta that by AD 1860 was the biggest livestock farm in northern Latvia including more than 1584 sheep (Enzeliņš, 1932). Because of intensive arable and livestock farming the landscape developed predominantly open characteristics, demonstrated as such in two historical drawings from AD 1800 (Figure 6(a)) and AD 1866 (Figure 6(b)). Both reveal large areas of open fields with isolated stands of tree and point to the presence of a variety of livestock, including cattle and sheep. The palaeorecord from Lake Trikātas, characterised by high cultural indicators, high mineral content of the sediment and quartz grains, and low arboreal pollen concentration (Figure 3) shows a reliable reconstruction of land-use history during the 19^{th} century, although tree pollen percentages seem to be over-represented. Extensive land-use decreased after AD 1930 at Lake Trikātas as reflected by lower values of mineral matter content, magnetic susceptibility, quartz grains and cultural indicators. Meanwhile higher macrocharcoal frequencies may point to fire in the local vicinity that can be associated with establishment of a distillery, brick kiln and a dairy next to the lake.

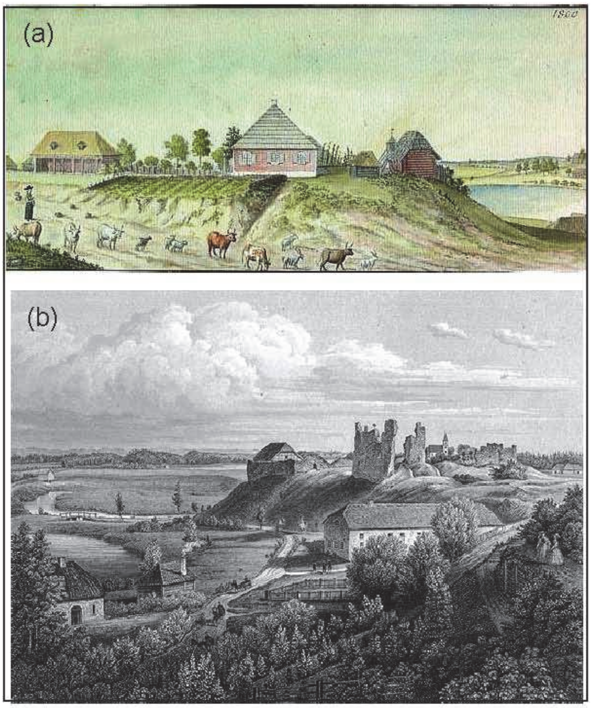

Figure 6. Drawing from (a) AD 1800 by Broce J.K. "*Ansicht des Hofes Trikaten von der Abendseite*" taken from western part of the lake Trikātas, adjacent to remnants of Trikātas castle, Lake Trikātas on the right side of the drawing and, (b) engraving from AD 1886 by Stavenhagen W.S. showing landscape of surroundings south west direction from diary, Lake Trikātas on the left side of engraving.

Conclusions

The study described in this paper, when set in the context of other palynological studies from Livonia, demonstrate the varied spatial and chronological histories of medieval land-use. The picture beginning to emerge from palynological studies suggests that the crusades and conquest of former tribal lands was not accompanied by significant impacts on rural landscapes. Colonization was limited to the principal urban centres whilst native communities continued to follow indigenous patterns of land-use; agricultural intensification is not widely apparent until the 14th century, a century or more after the initial crusades. However, the palaeoenvironmental data from Lake Trikātas demonstrates significant woodland clearance and intensified land-use from the early 13th century immediately following the crusades, which we interpret as reflecting the important role played by the castle and its hinterland in organising the production, storage and redistribution of local agricultural produce.

Trikāta was located on one of the main north-south routes through Livonia within a relatively stable part of the order state, and is likely to have performed a key provisioning role as suggested by later 14th century documentary sources.

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